

The quest for the proton spin with the polarized proton collider RHIC

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Outline

- What is “proton spin”?
- The spin program at RHIC
- PHENIX experiment
- Results
 - ΔG
 - Δq
 - Transverse spin
- Next steps
- Summary

What is the origin of the matter?

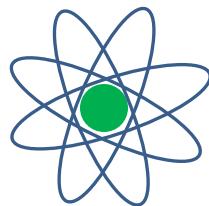


10^{-7} cm

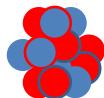


- Water molecule
- Atom
- Nucleus
- Proton
- Quark

10^{-8} cm



10^{-12} cm



- Quark is an elementary particle (so far)
- Quark doesn't exist by stand-alone in the world.

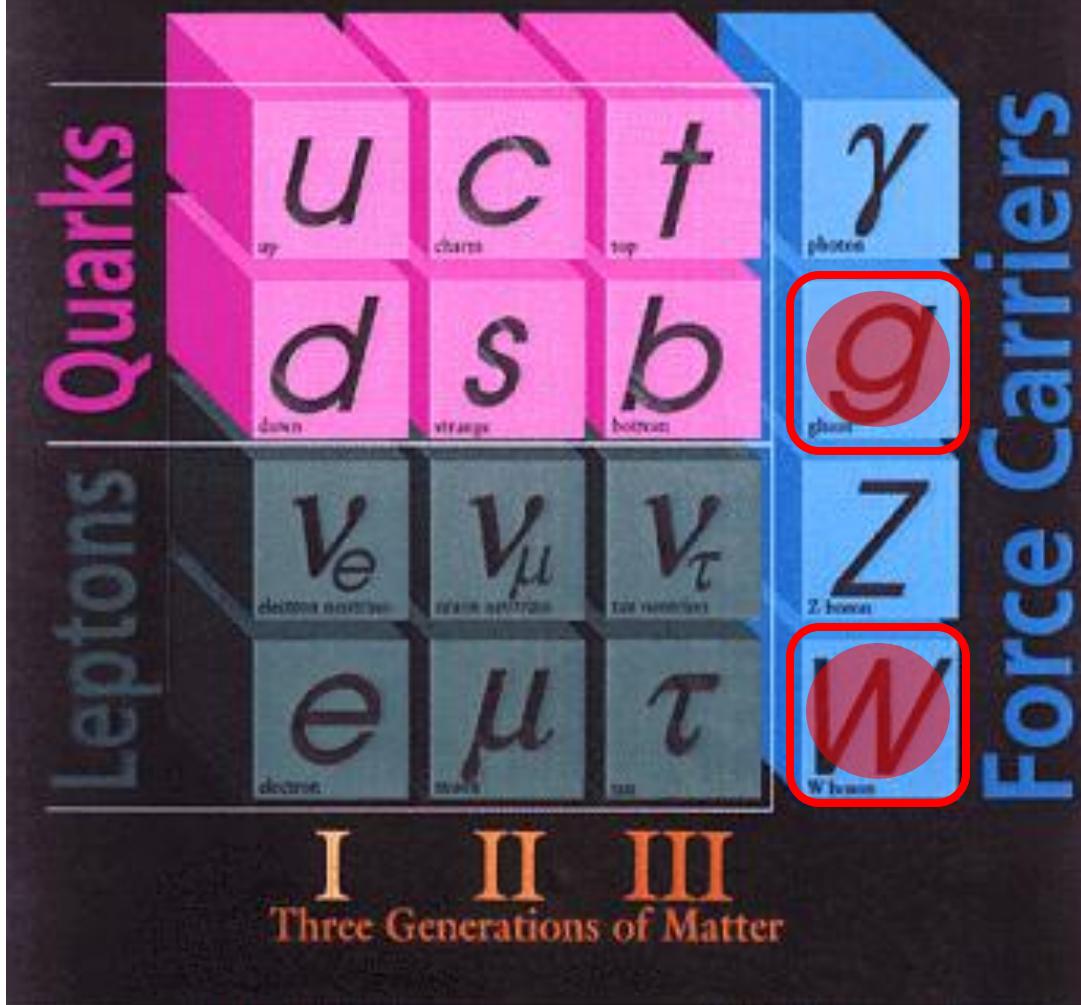
10^{-13} cm



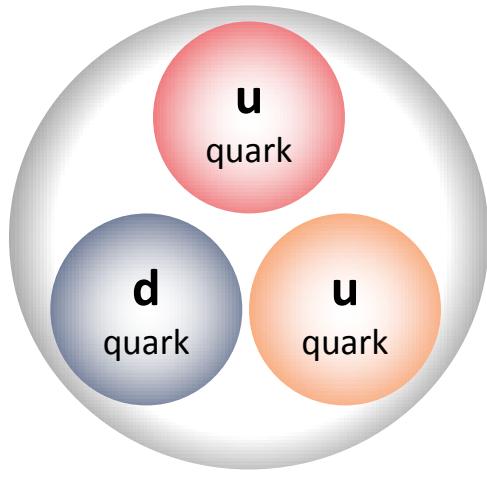
0 ($<10^{-18}$ cm)



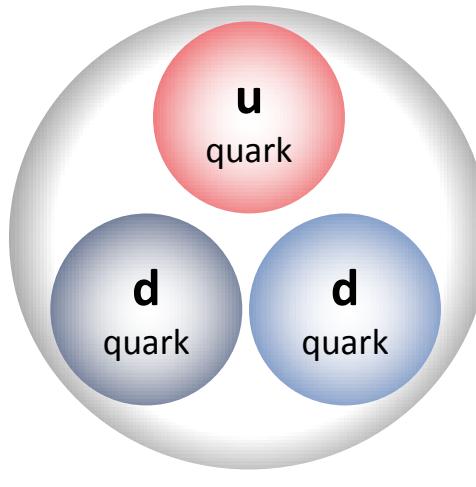
ELEMENTARY PARTICLES



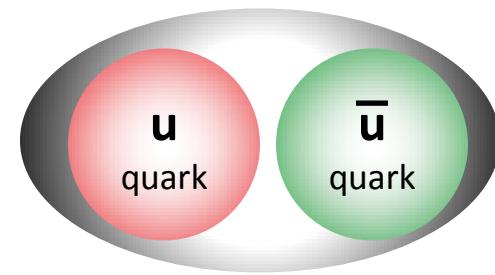
Friends of proton (hadron)



Proton



neutron

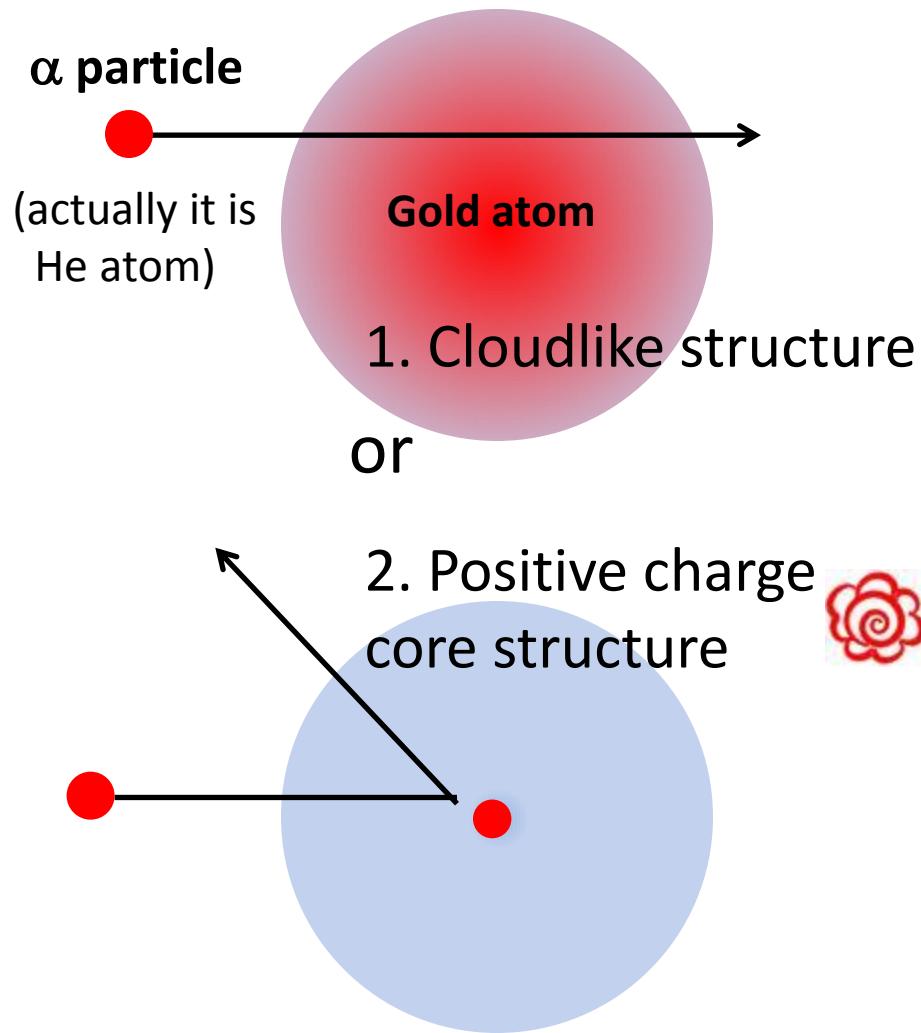


Neutral π particle

- Quarks form a hadron.
- Proton, neutron, and other short-lived particles.

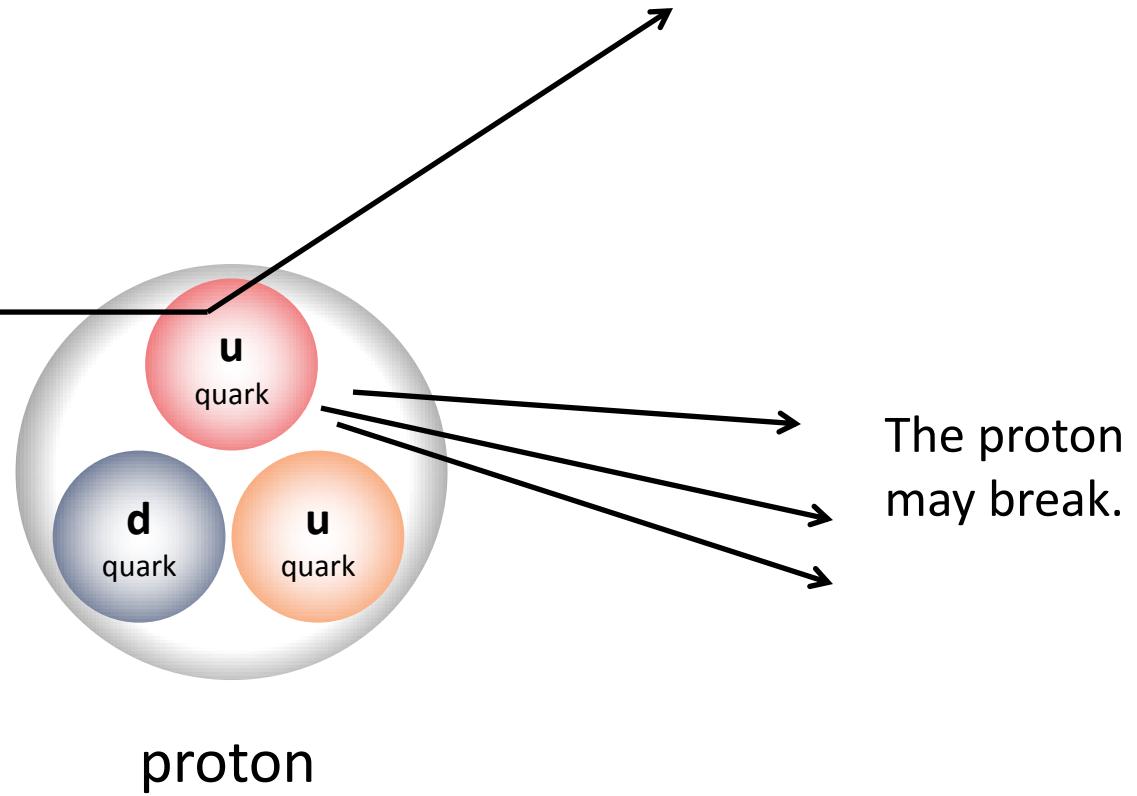
How to see inside (Scattering)

- Rutherford scattering, 1911
- Shot α particle to gold atoms



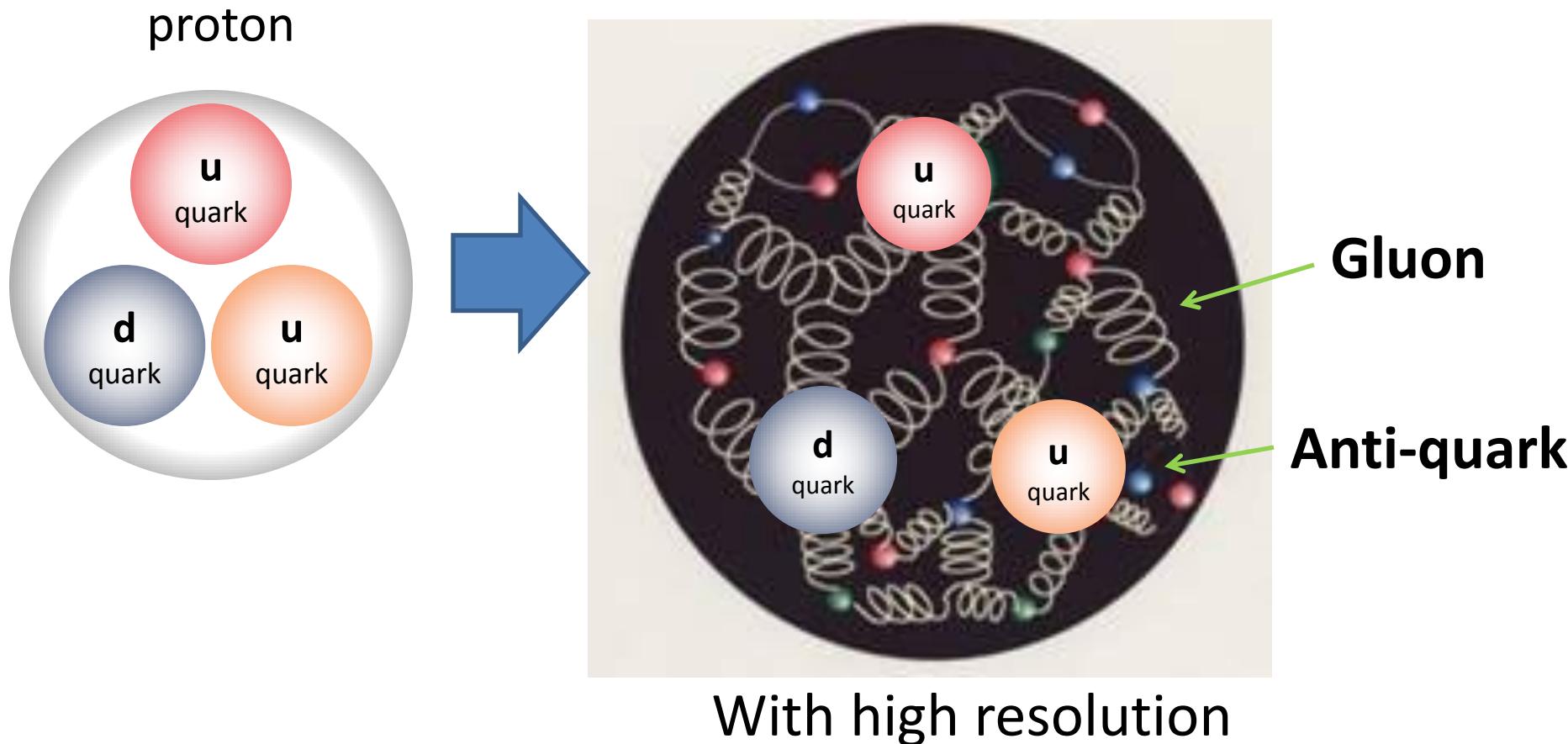
Inside the proton

ex) Electron

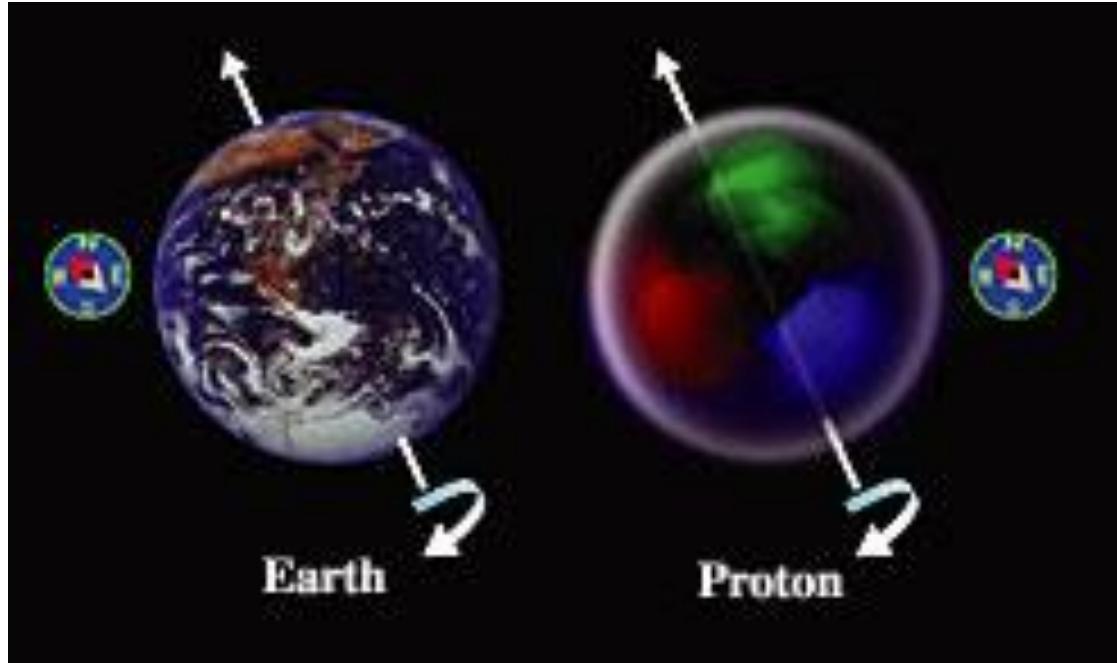


Proton is more complicated

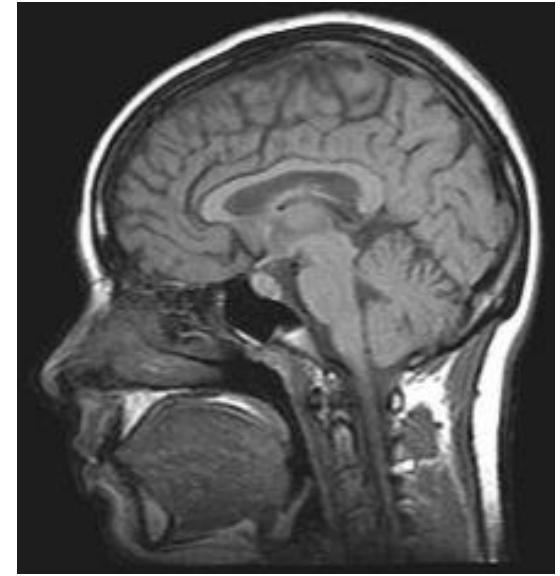
From electron scattering experiments,



“Spin” of proton



- Some say it's like a rotation.
(the intrinsic angular momentum)
- Size: $1/2$ (with a unit of $\hbar=h/2\pi$)
- It is 2 directions (+/-) along the axis



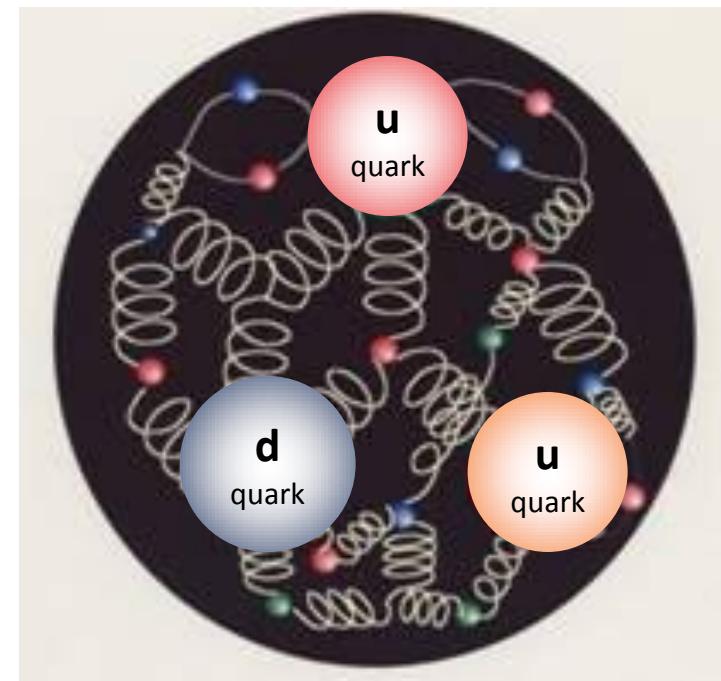
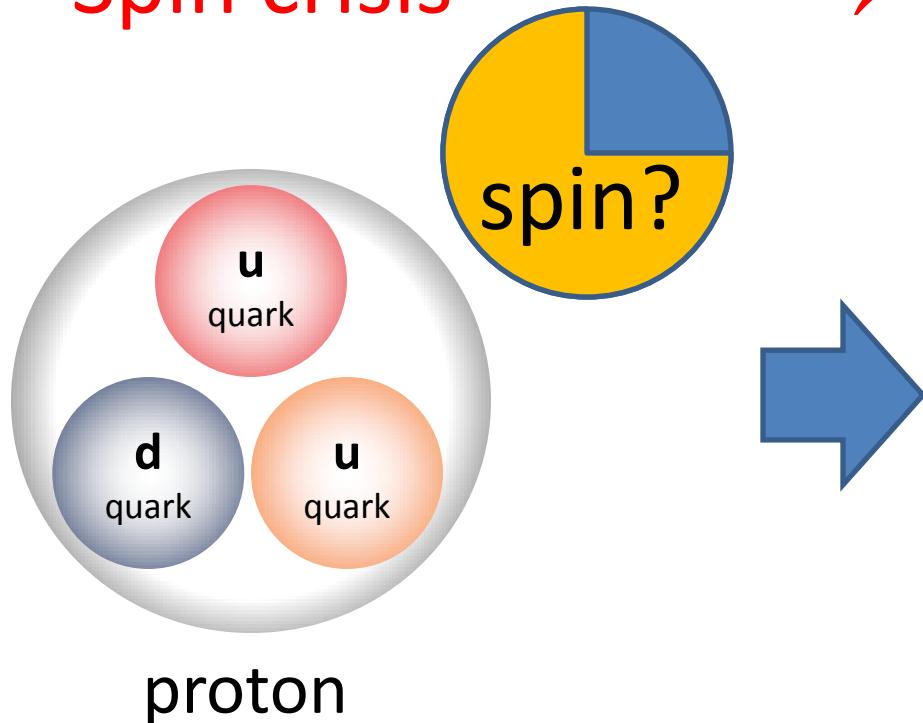
It is already used.
(ex. MRI)

What builds spin $\frac{1}{2}$?

(In late 1980's) e+p, μ +p scattering in SLAC/CERN/DESY/JLAB

- Contribution of quark spin to the proton spin
 - Is only $\sim 25\%$.

Spin crisis → Spin puzzle



How about gluons? (\rightarrow RHIC)

Proton spin =

(quark spin) + (gluon spin) + (angular momentum)

$$\frac{1}{2} \Delta \Sigma$$

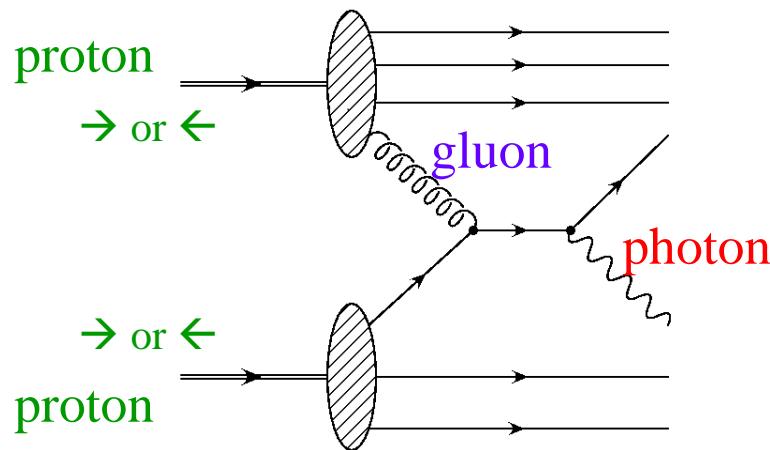
$$\Delta G$$

$$L$$

$\sim 25\%$

Direct

p+p scattering





RHIC

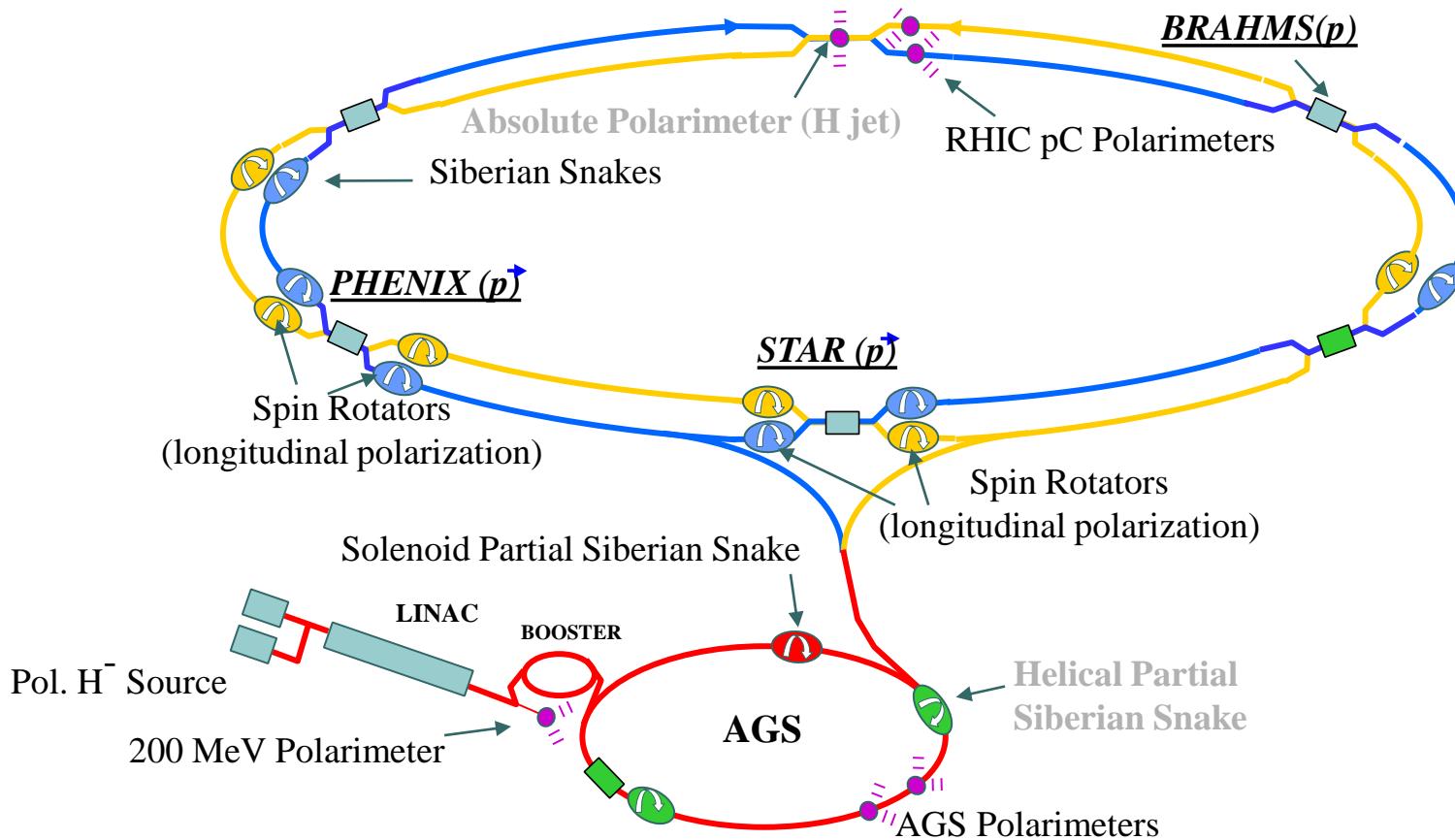
BOOSTER

LINAC

AGS

TANDEMS

Realization of polarized $p+p$ collider



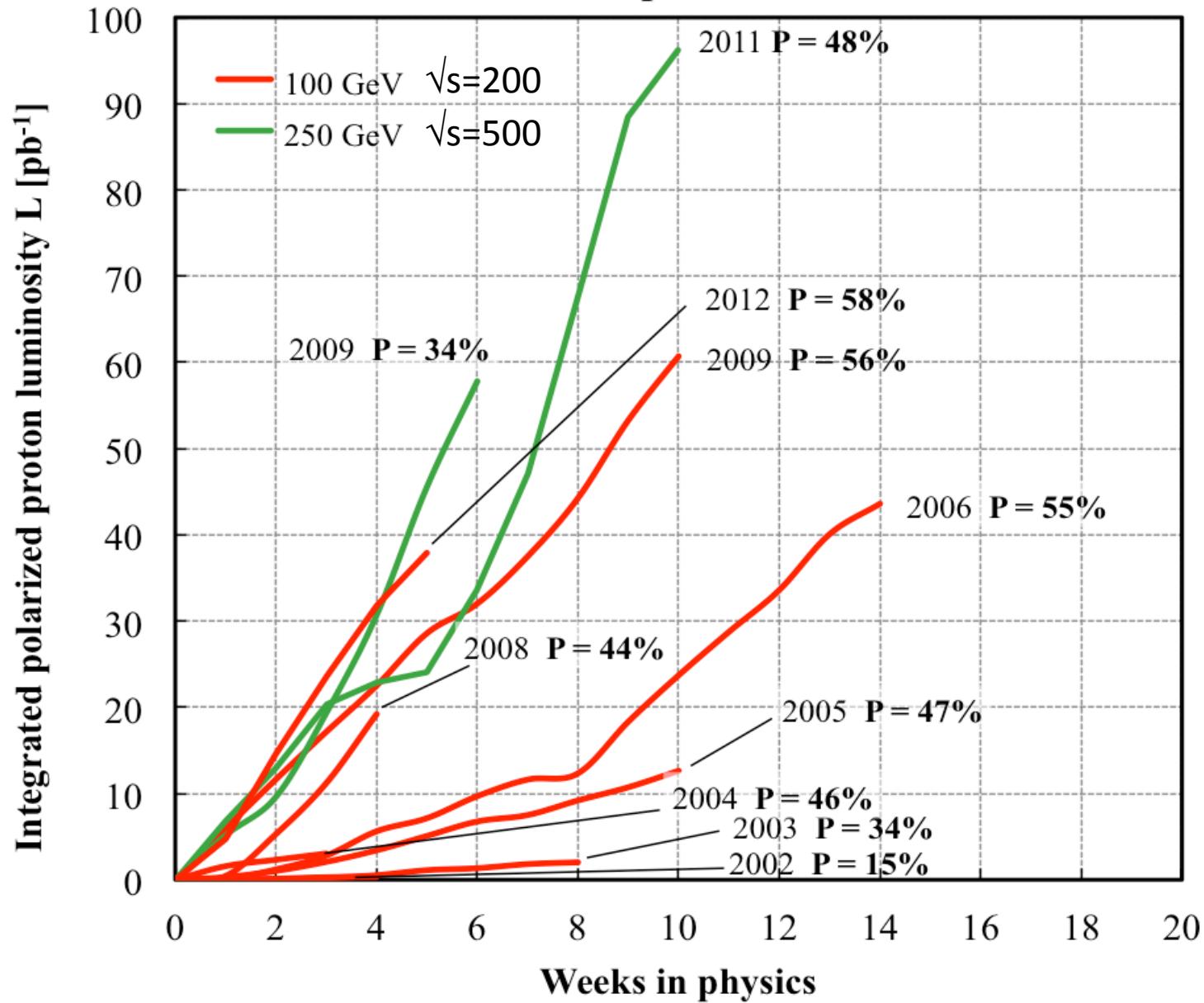
- Keep the original polarization
- Polarimeter

Relativistic Heavy Ion Collider?

- 1991 RHIC construction
 - 1993 Spin program approval
 - 1995 RIKEN-BNL agreement. Start the special magnet construction, polarimeter development.
 - 2002 First polarized proton proton collision ($\sqrt{s}=200\text{GeV}$)
 - 2009 Start $\sqrt{s}=500\text{GeV}$ spin program

← I joined PHENIX in 2001

Polarized proton runs



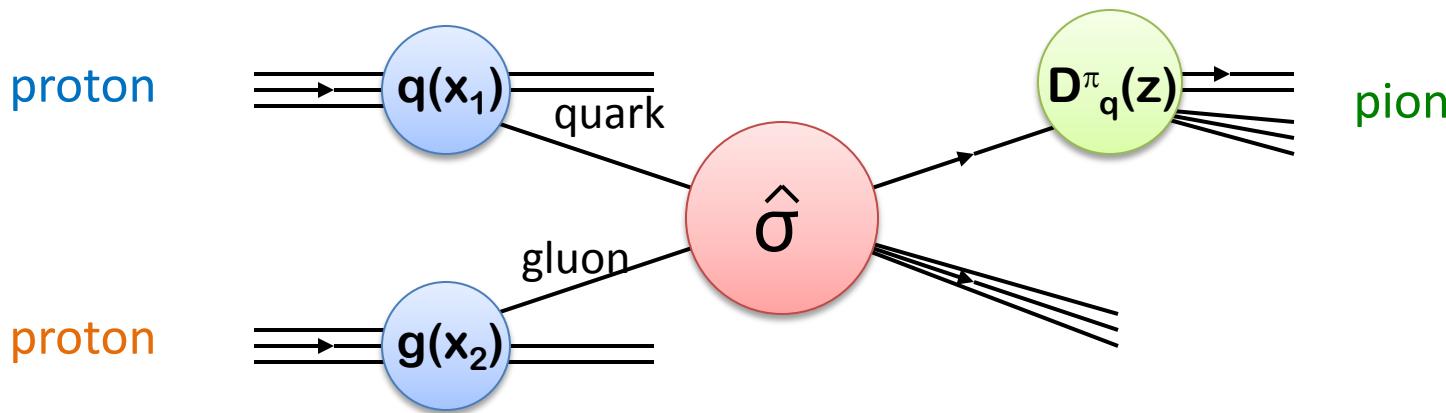
Summary of the introduction

- Proton is made of quarks, anti-quarks, and gluons.
- Contributions of quarks and anti-quarks are small to the proton spin.
- RHIC is a strong tool to the proton spin puzzle.

RHIC SPIN PROGRAM (3 TOPICS)

ΔG ,
quark flavor dependence,
transverse spin (A new tool)

1. Gluon spin polarization

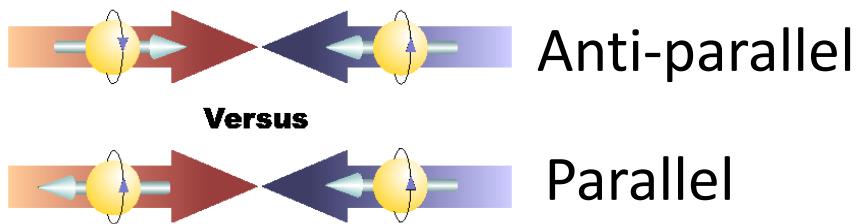


$$\sigma(pp \rightarrow \pi X) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg \rightarrow qg}(\hat{s}) \otimes D_q^\pi(z)$$

from DIS

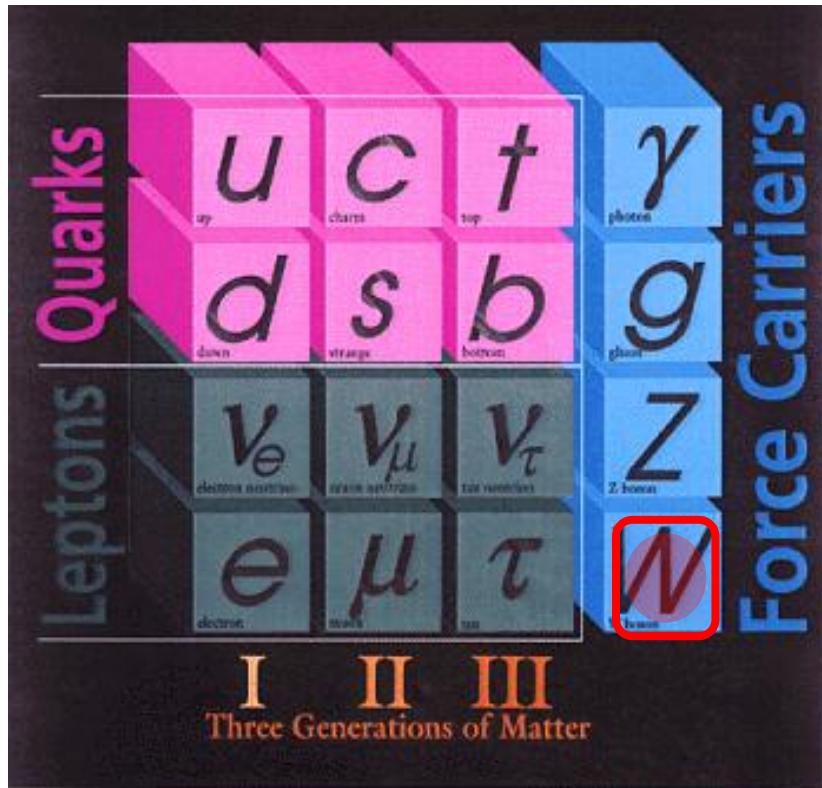
from pQCD

from e^+e^-



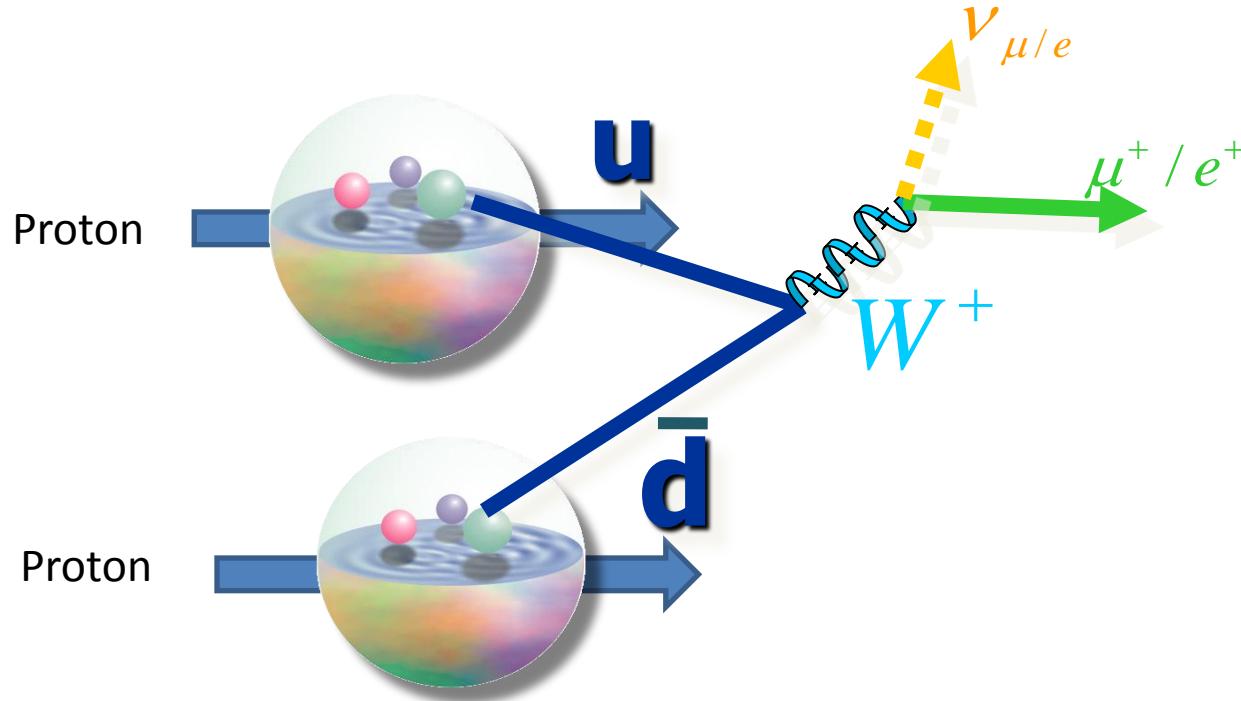
Large gluon polarization \rightarrow Large double spin asymmetry

2. Quark polarization (flavor dependent) via W boson production



- With RHIC top energy ($\sqrt{s}=500\text{GeV}$), we can use very heavy W bosons as a tool.

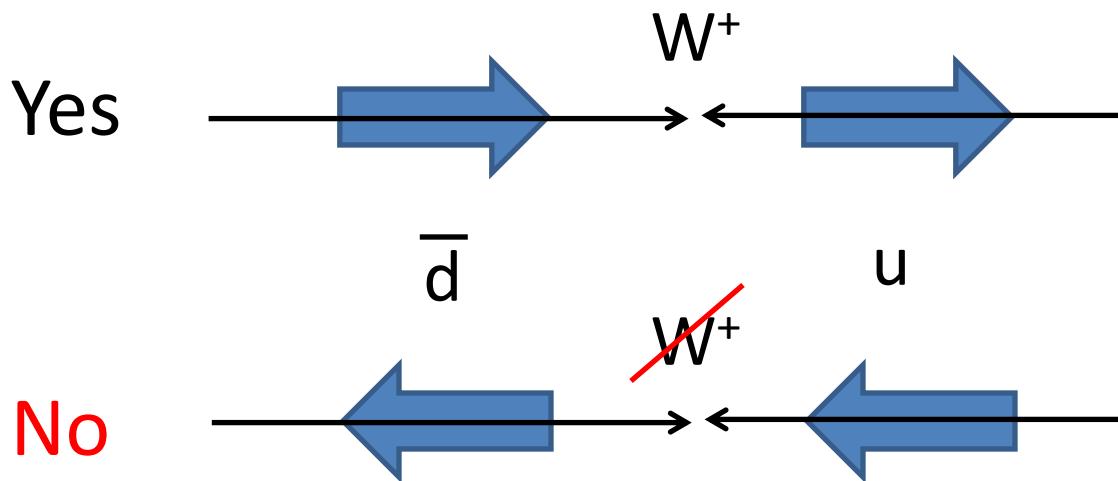
Quark flavor



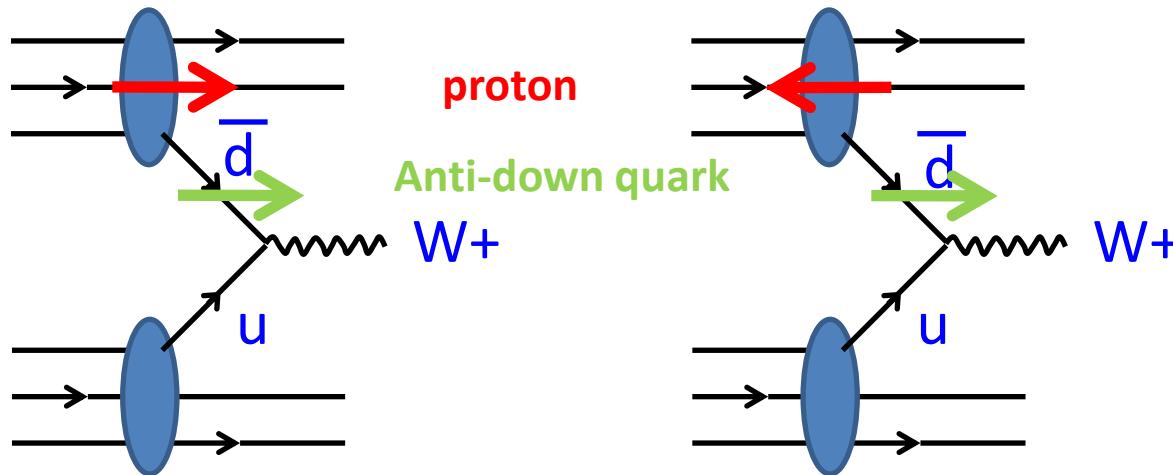
- W^+ : from **up** and **anti-down** quark ($u\bar{d}$)
- W^- : from **anti-up** and **down** quark ($\bar{u}d$)
- The charge determines the quark pair.

Quark polarization

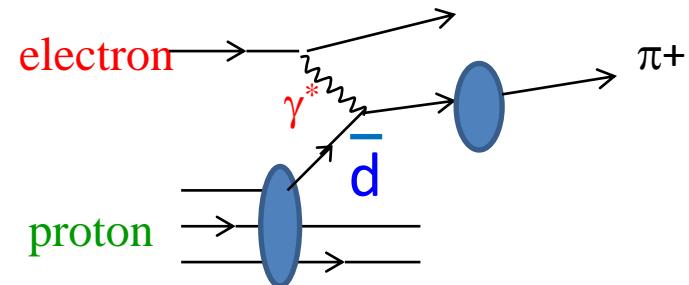
- “Weak interaction” has the maximum parity violation. It means the quark spin direction is fixed.



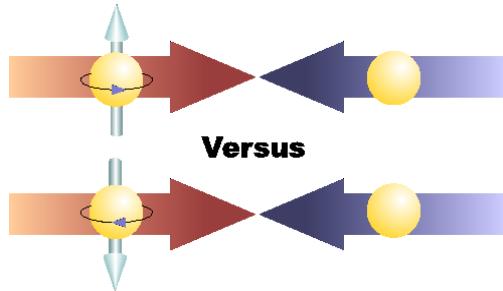
Proton spin dependence



- The single spin asymmetry (A_L) of the W^+ production is sensitive to the anti-down quark polarization.
- Others rely on the knowledge of fragmentation.



3. A new way to test QCD (the theory of strong interaction)

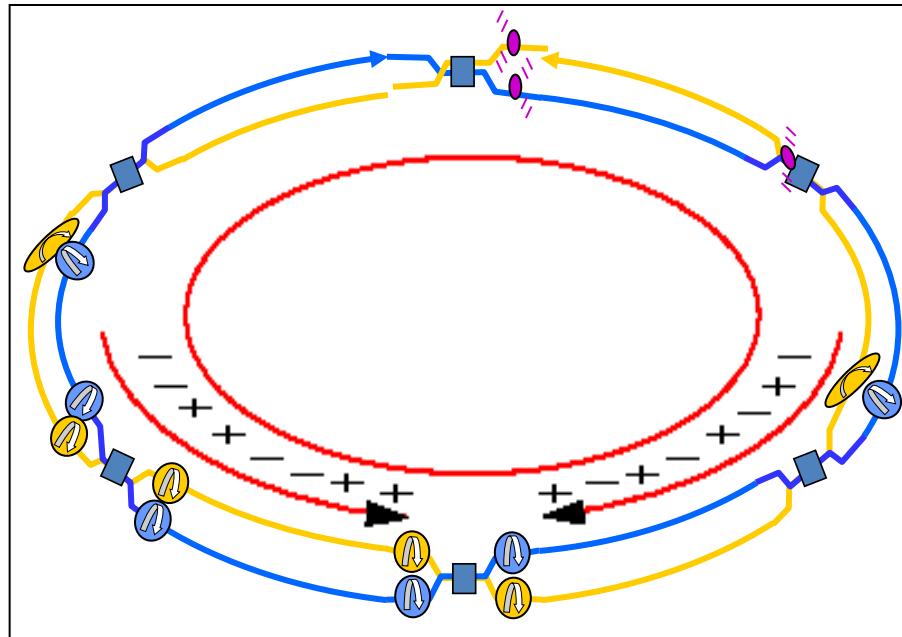


- It is related to the higher order pQCD effect.
- Intuitively, it is a transverse motion.
- It has to be related to the orbital momentum.
- It is a hot topic in both experiment and theory.



EXPERIMENT

Experimental essence

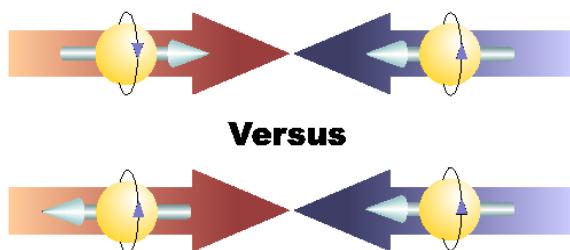


Each bunch is assigned different polarization direction. It reduces the systematics of detector time dependence.

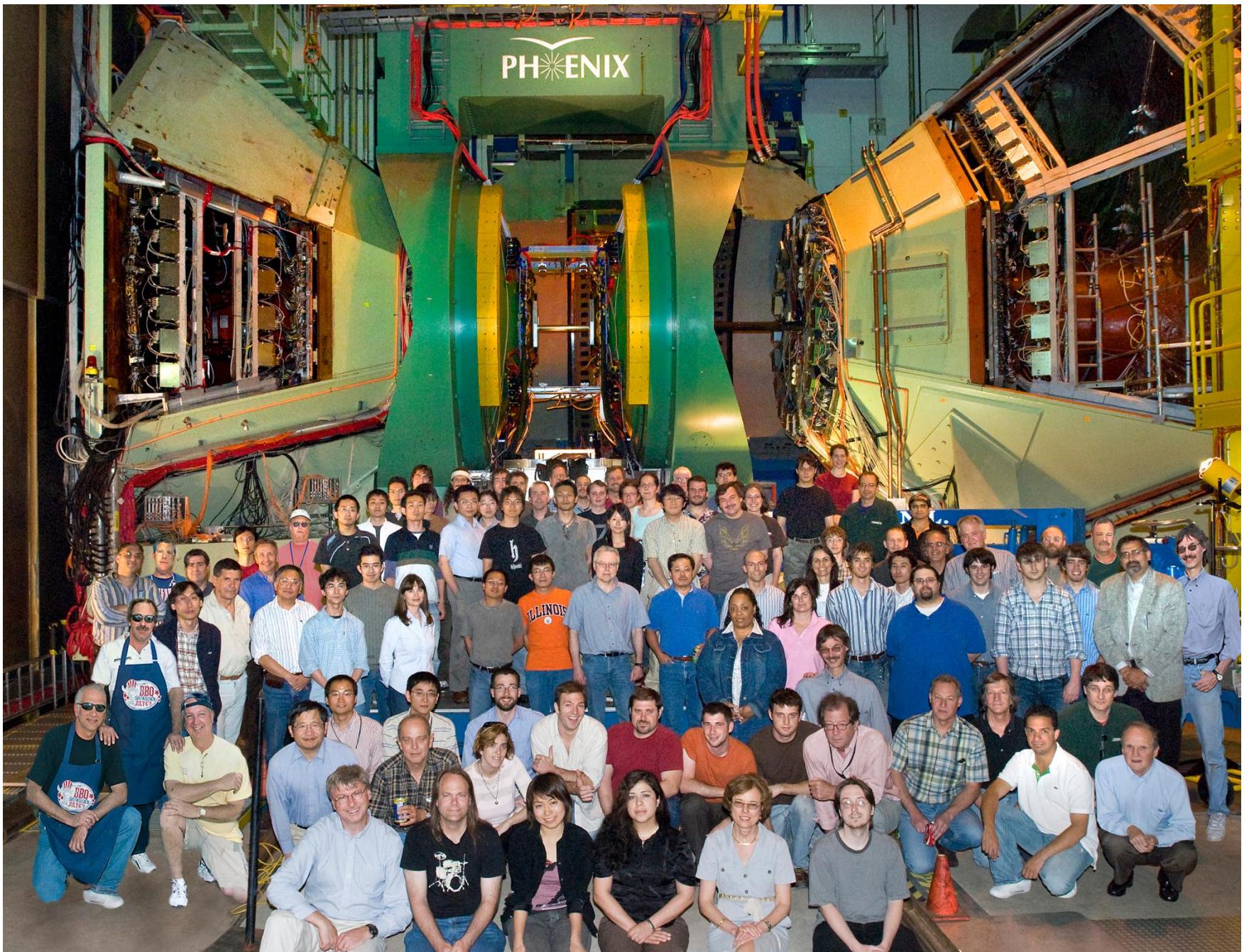
- Spin dependence of the interaction



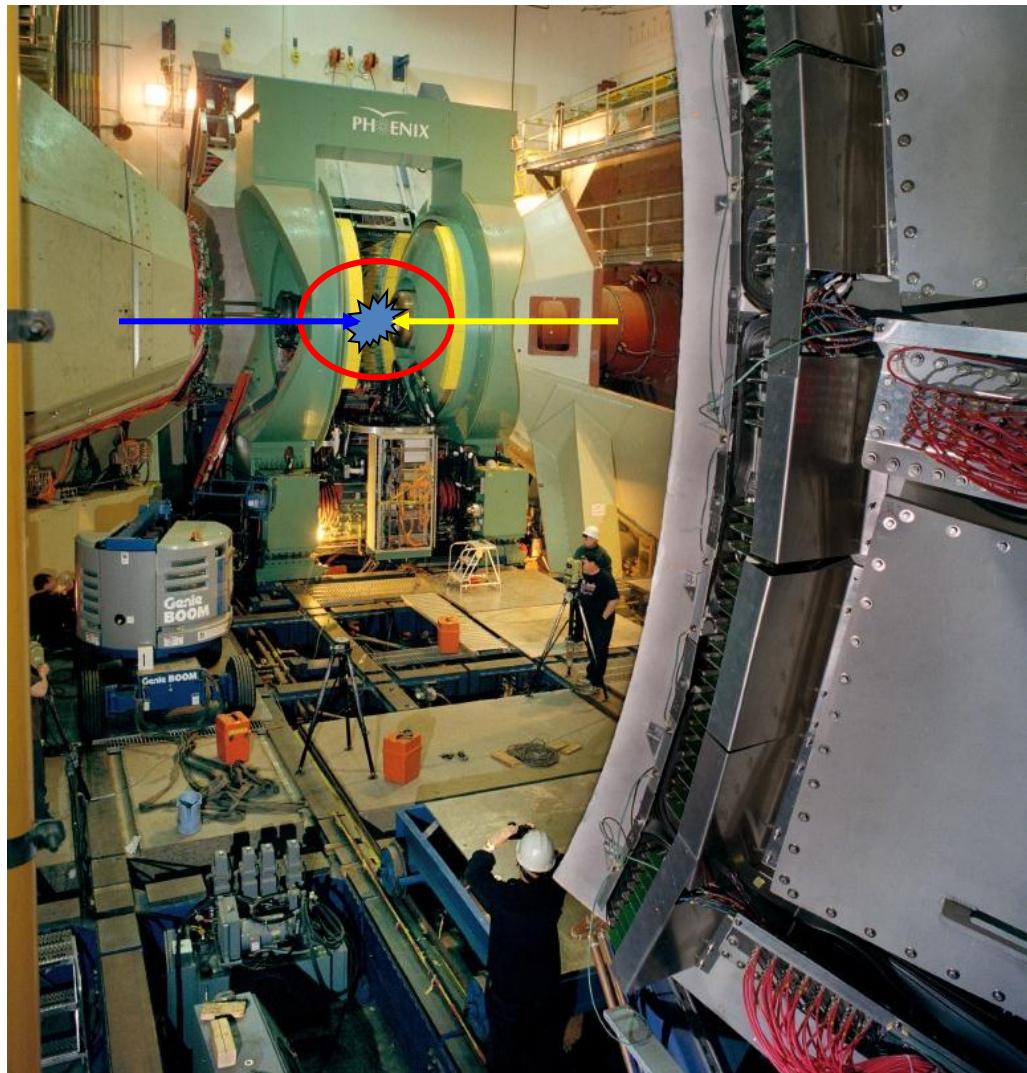
- Production rate
- Interaction rate (=Luminosity)



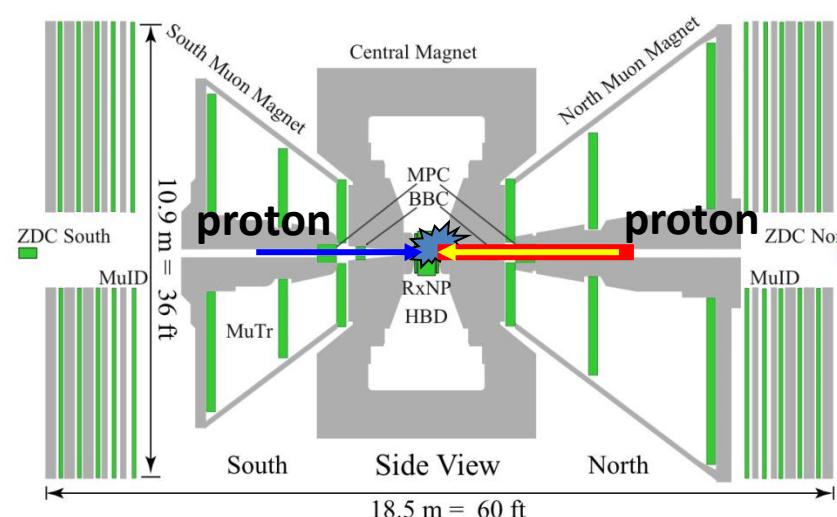
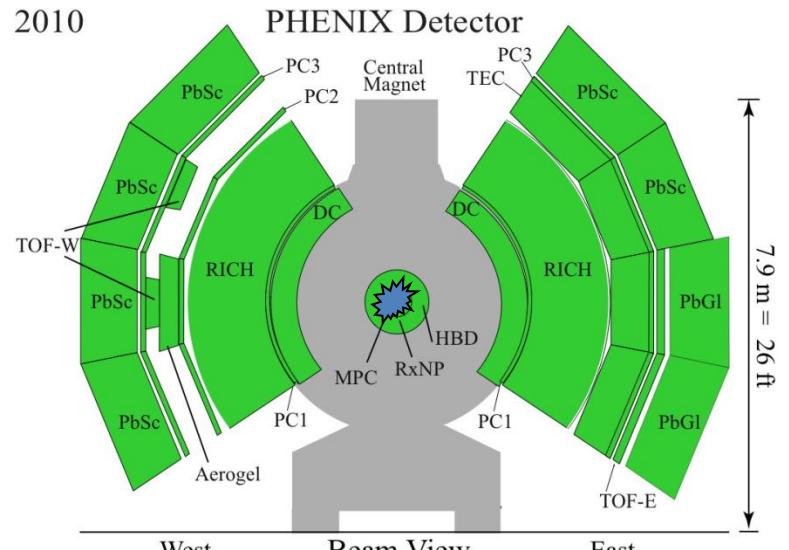
*) At minimum, relative rate is required.



PHENIX detector

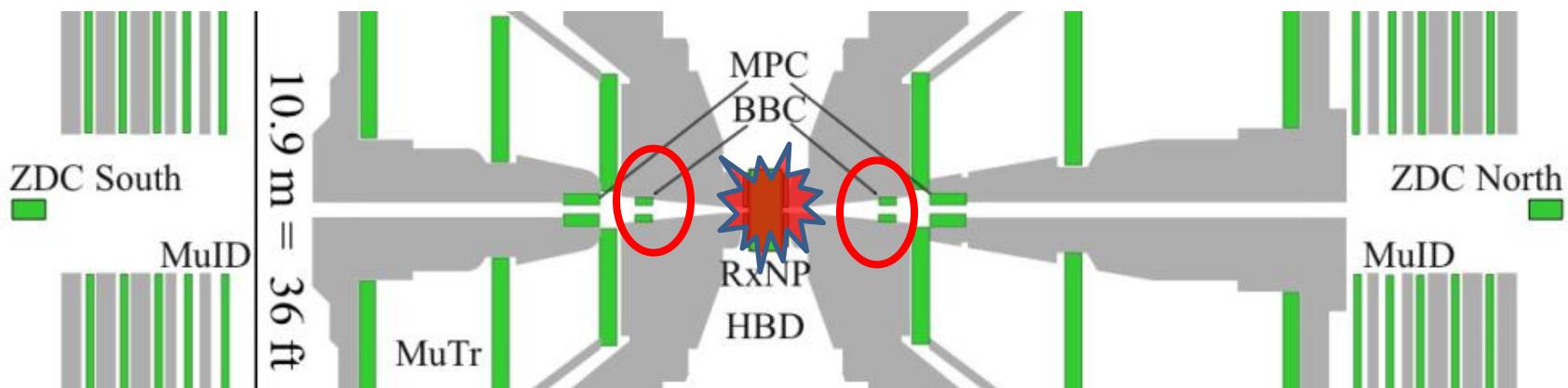
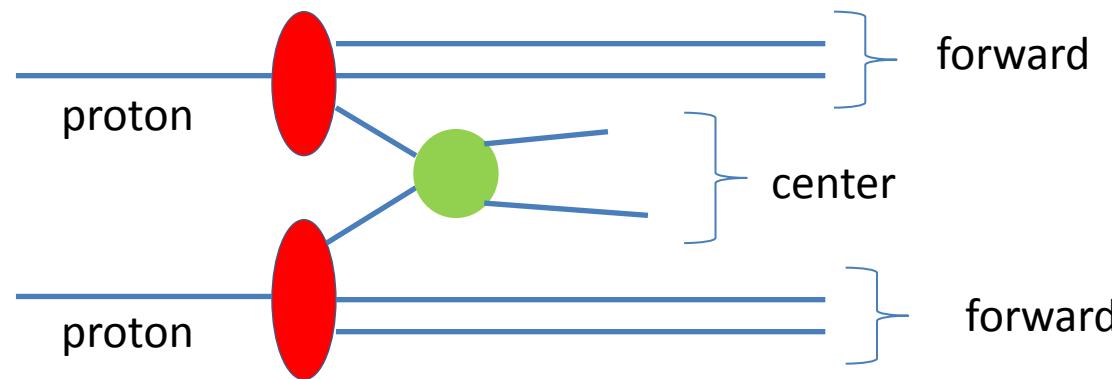


Central arms + Forward muon arms



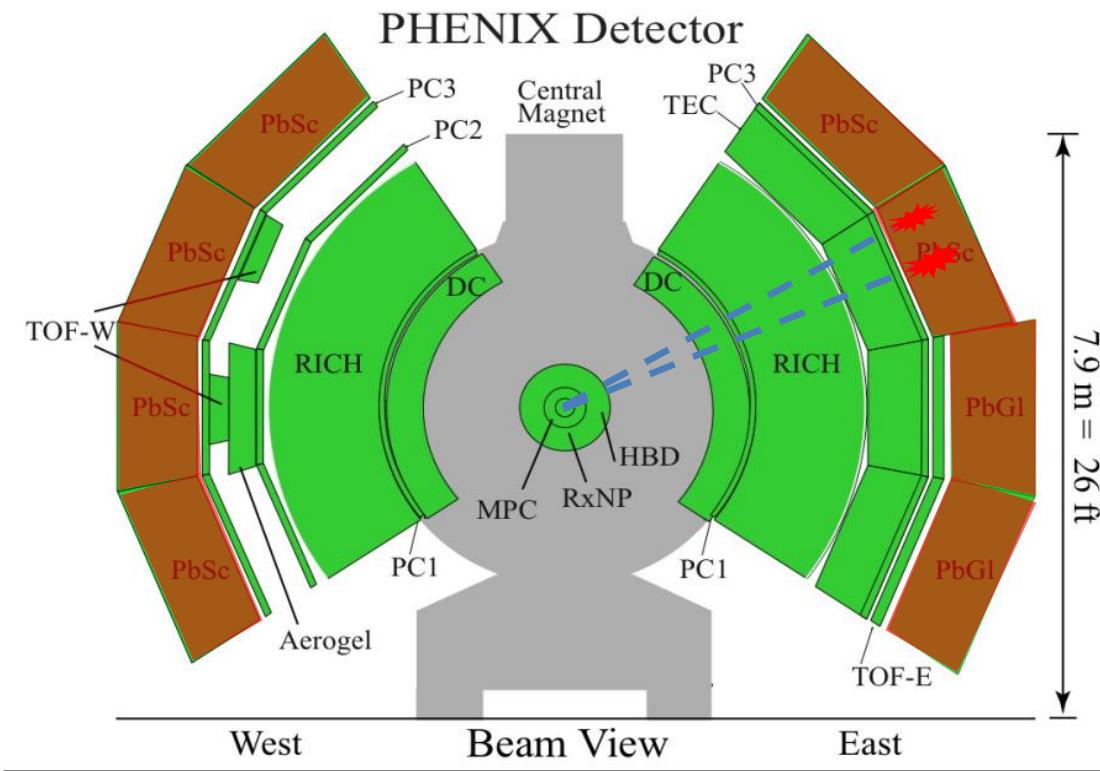
Interaction rate (=Luminosity)

- From the fragments of nuclear interaction.



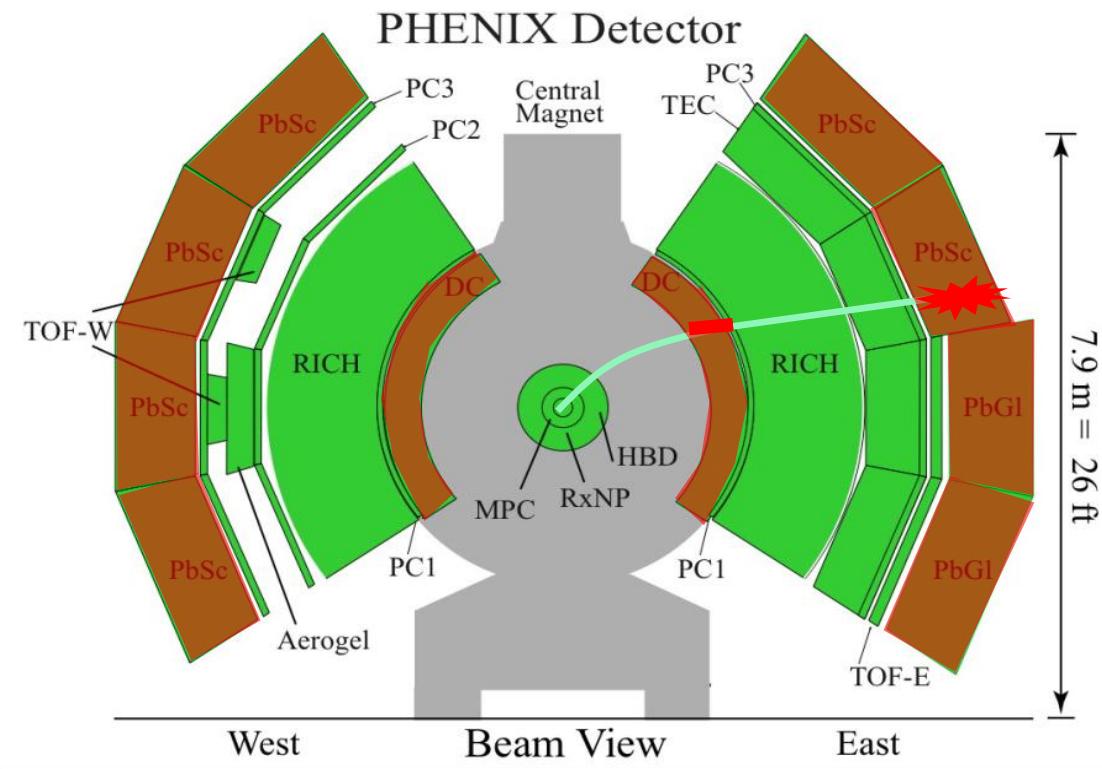
(Ex.1) Production rate measurement

- Electromagnetic calorimeter
 - Detection of 2 photons from π^0 particle decay (most abundant process)



(Ex.2) Production rate measurement

- Electromagnetic calorimeter + Tracking (Drift chamber/Pad chamber)
 - Detection of electron from W-boson decay.

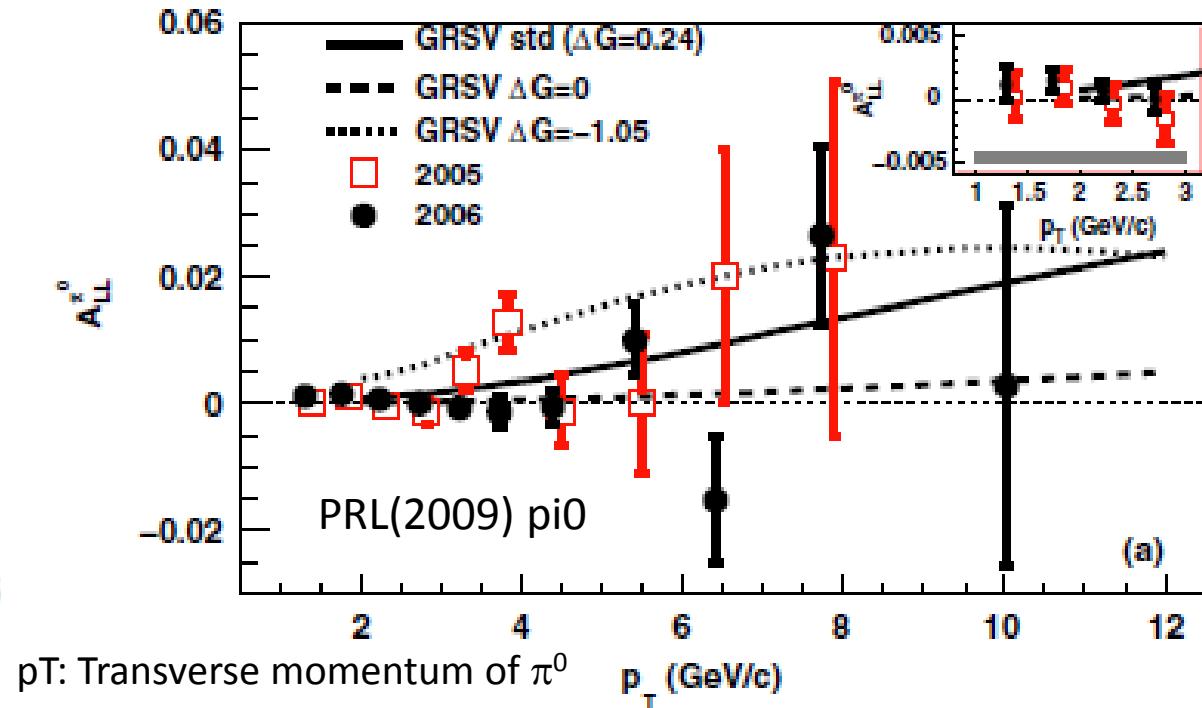
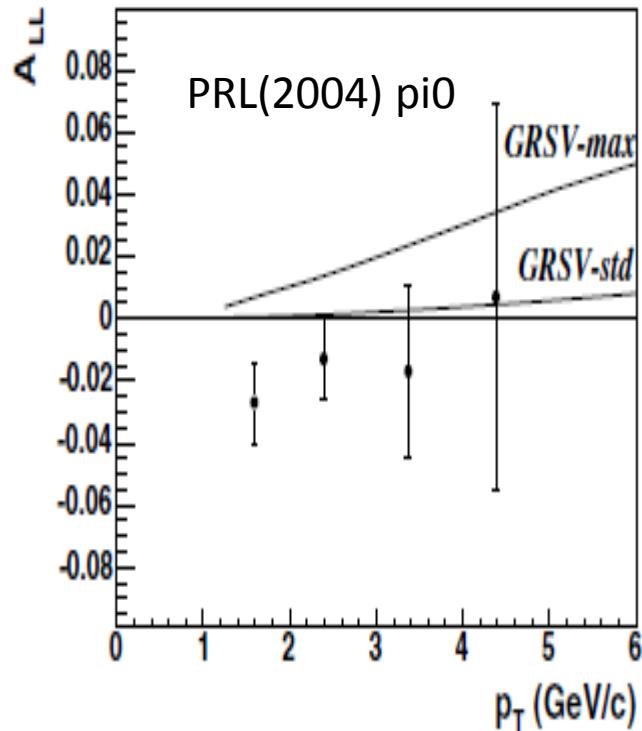
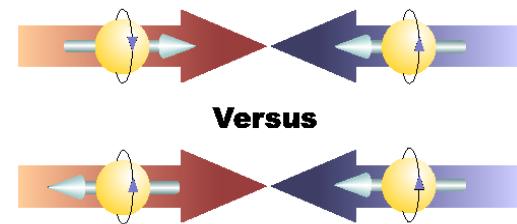


RESULTS

ΔG ,
quark flavor dependence,
transverse spin

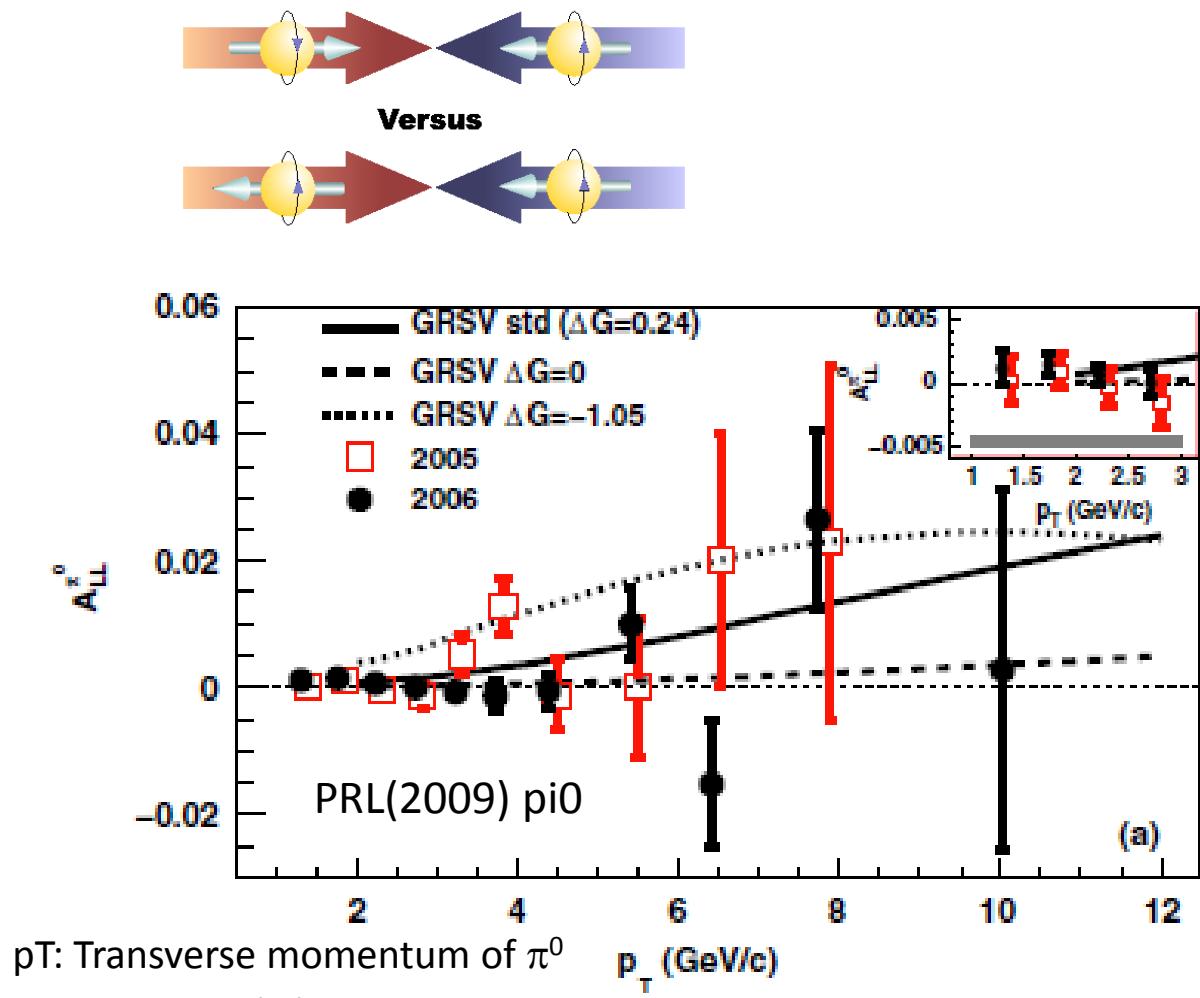
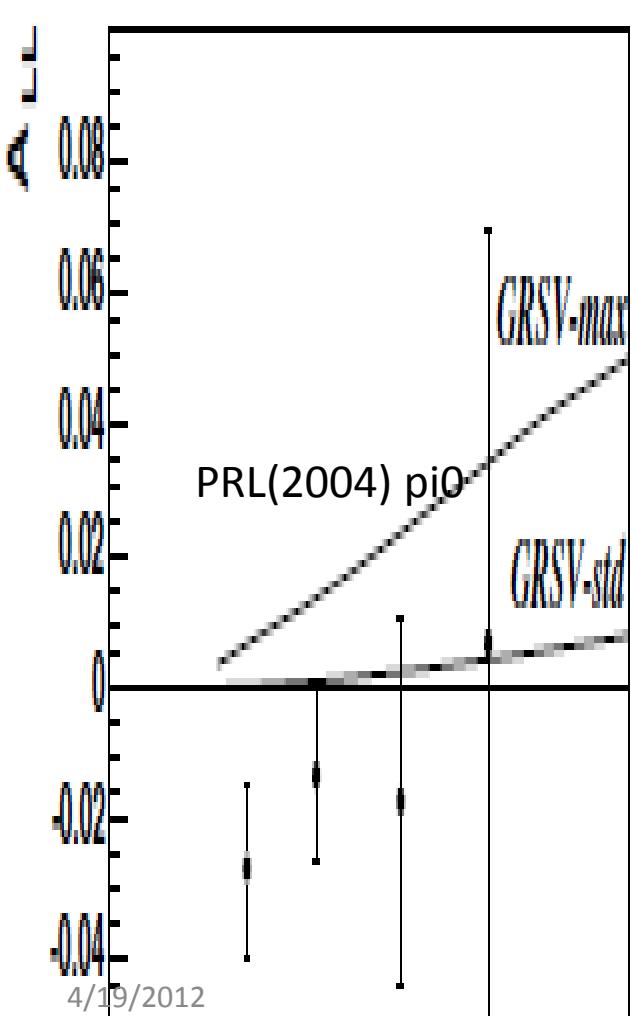
Gluon polarization is small

- From the measurement of double spin asymmetry (A_{LL}) of π^0 production



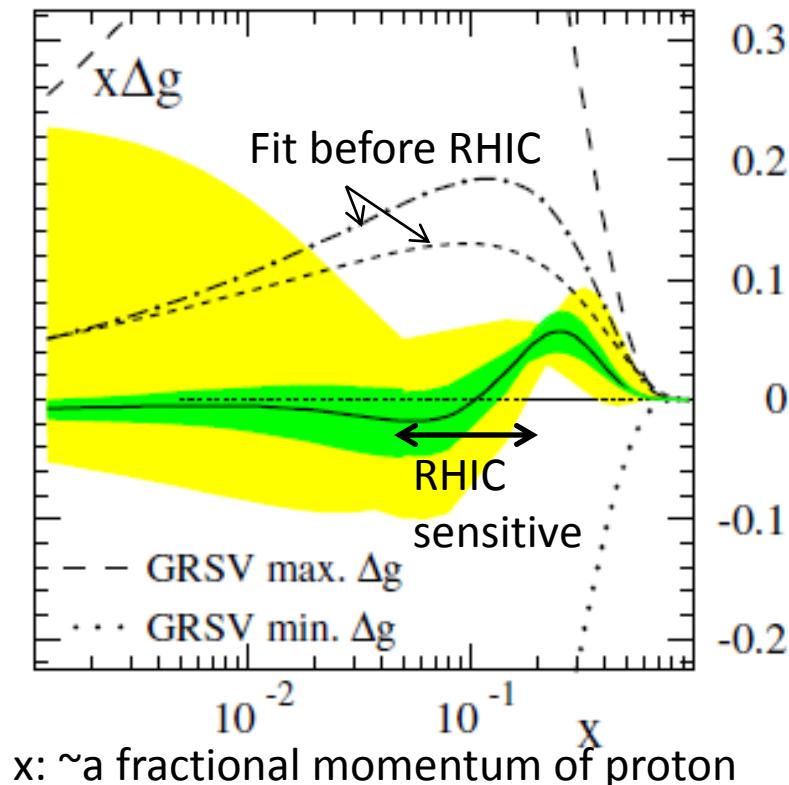
Gluon polarization is small

- A large polarization model is excluded.



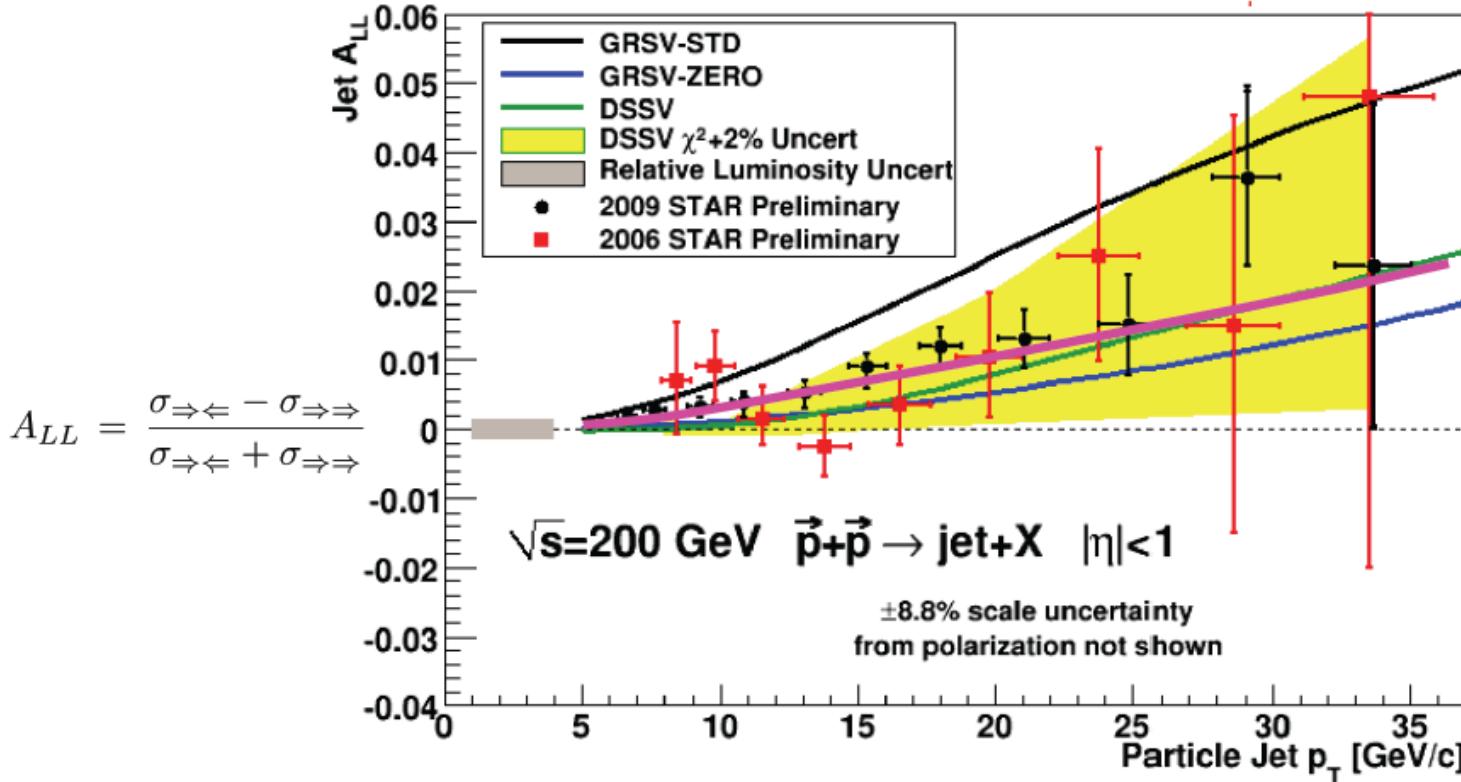
A node in Δg ?

- From a global analysis (DSSV group)
 - PHENIX + STAR + SIDIS + DIS
 - Δg is smaller than GRSV-std [$\Delta g = 0.4$ at $Q^2 = 1$ (GeV/c^2)²]
 - RHIC data are effective for $\Delta g(x)$ in $0.05 < x < 0.2$ region.
- de Florian, Sassot, Stratmann
and Vogelsang,
PRL 101, 072001 (2008).



Hint for non-zero ΔG

(3) New developments on Δg



DIS2012
Werner

- gives gluon with

$$\int_{0.05}^{0.2} dx \Delta g \approx 0.1$$

W BOSON



W BOSON MEASUREMENT AT PHENIX

PRL 106, 062001 (2011)

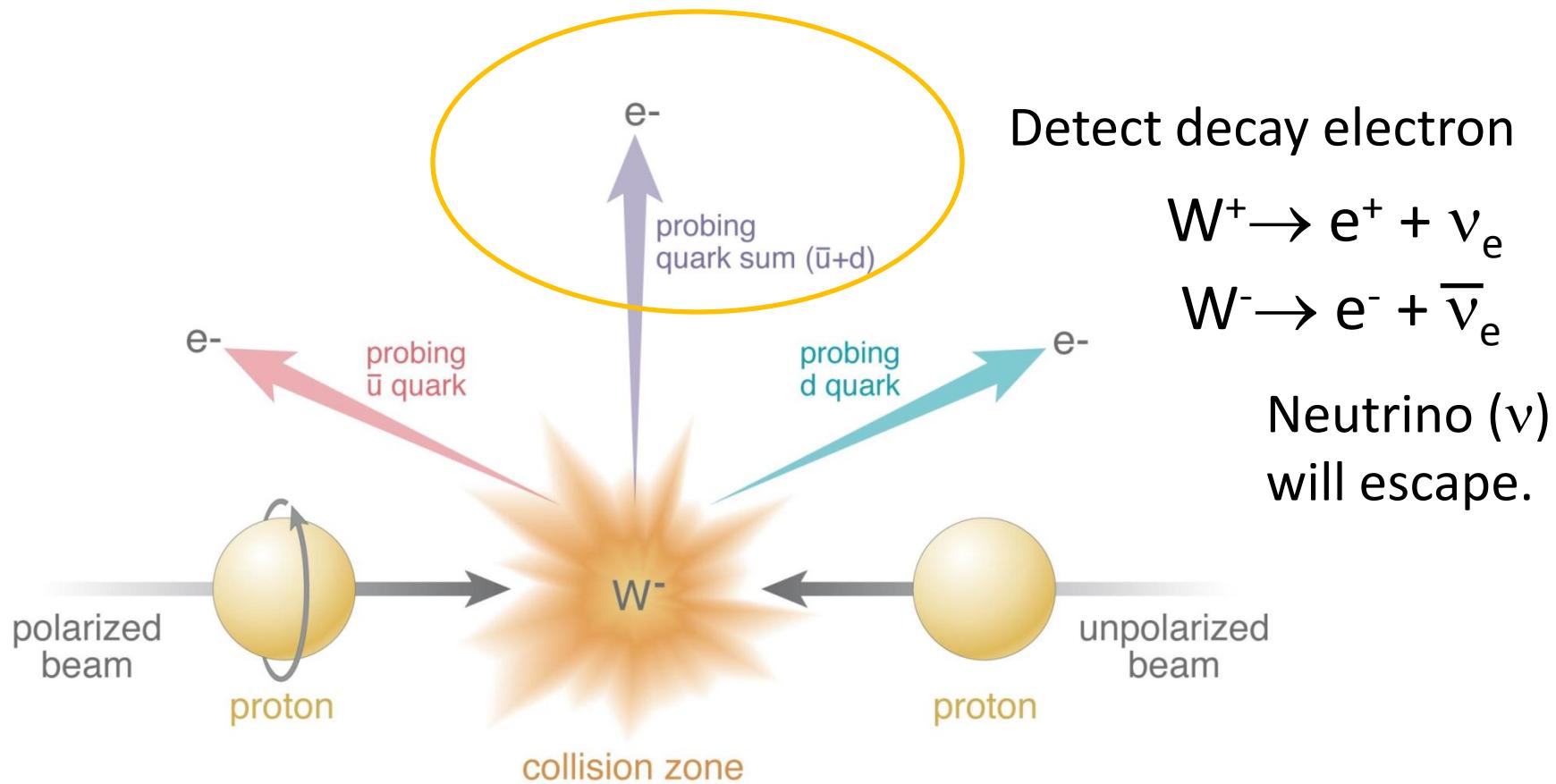
PHYSICAL REVIEW LETTERS

week ending
11 FEBRUARY 2011

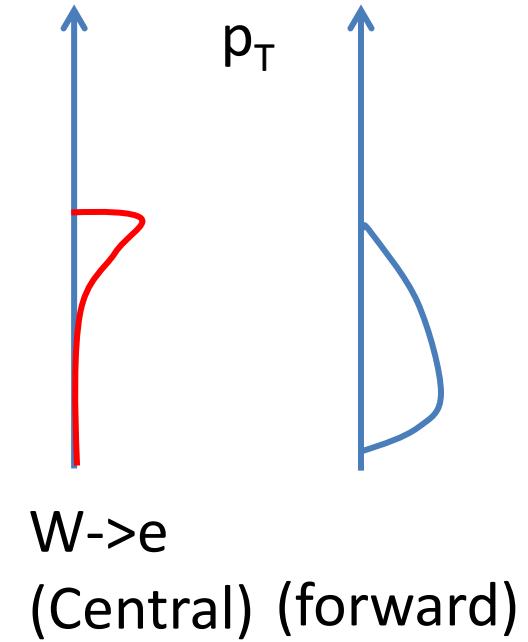
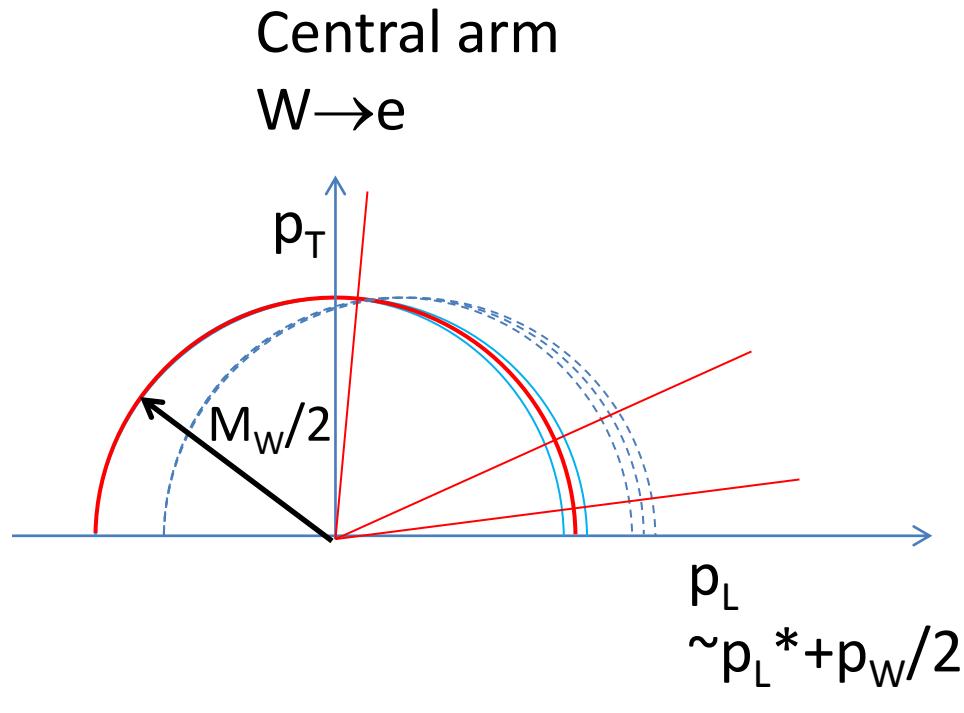
Cross Section and Parity-Violating Spin Asymmetries of W^\pm Boson Production in Polarized $p + p$ Collisions at $\sqrt{s} = 500$ GeV

A. Adare,¹¹ S. Afanasiev,²⁵ C. Aidala,³⁴ N. N. Ajitanand,⁵⁶ Y. Akiba,^{50,51} R. Akimoto,¹⁰ J. Alexander,⁵⁶ H. Al-Ta'ani,⁴⁴ K. R. Andrews,¹ A. Angerami,¹² K. Aoki,⁵⁰ N. Apadula,⁵⁷ E. Appelt,⁶¹ Y. Aramaki,¹⁰ R. Armendariz,⁶ E. C. Aschenauer,⁵ T. C. Awes,⁴⁶ B. Azmoun,⁵ V. Babintsev,²¹ M. Bai,⁴ B. Bannier,⁵⁷ K. N. Barish,⁶ B. Bassalleck,⁴³ A. T. Basye,¹ S. Bathe,⁵¹ V. Baublis,⁴⁹ C. Baumann,³⁹ A. Bazilevsky,⁵ R. Belmont,⁶¹ J. Ben-Benjamin,⁴⁰ R. Bennett,⁵⁷ A. Berdnikov,⁵³ Y. Berdnikov,⁵³ D. S. Blau,³⁰ J. S. Bok,⁶³ K. Boyle,⁵¹ M. L. Brooks,³⁴ D. Broxmeyer,⁴⁰ H. Buesching,⁵ V. Bumazhnov,²¹ G. Bunce,^{5,51} S. Butsyk,³⁴ S. Campbell,⁵⁷ A. Caringi,⁴⁰ P. Castera,⁵⁷ C.-H. Chen,⁵⁷ C. Y. Chi,¹² M. Chiu,⁵ I. J. Choi,^{22,63} J. B. Choi,⁸ R. K. Choudhury,³ P. Christiansen,³⁶ T. Chujo,⁶⁰ O. Chvala,⁶ V. Cianciolo,⁴⁶ Z. Citron,⁵⁷ B. A. Cole,¹² Z. Conesa del Valle,³² M. Connor,⁵⁷ M. Cronin,¹⁵ T. Csanak,²⁸ S. Daigeler,^{31,50} A. Datta,³⁸ C. David,⁵

Measurement of W boson decay



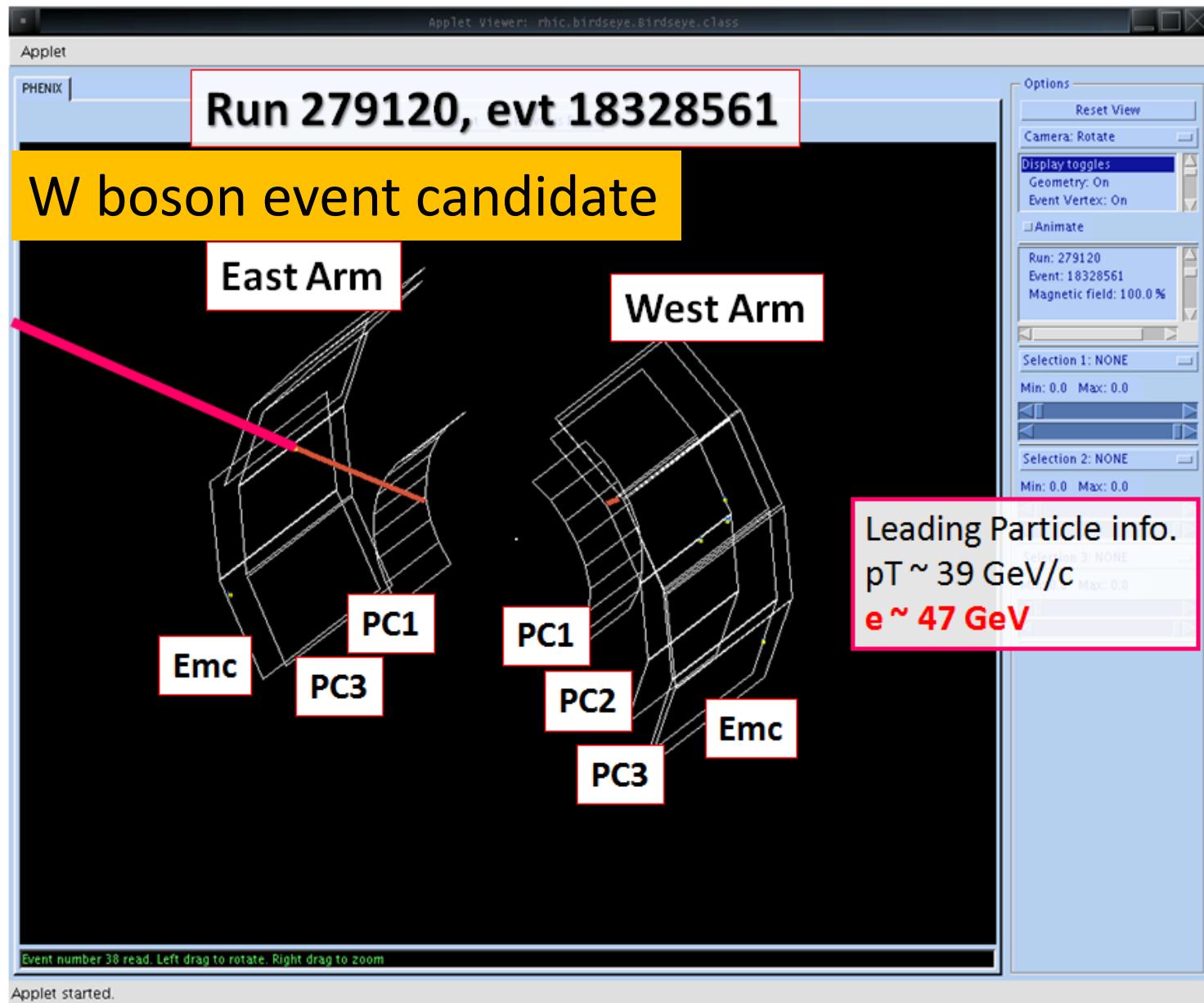
$W \rightarrow e\nu$, 2 body decay signal



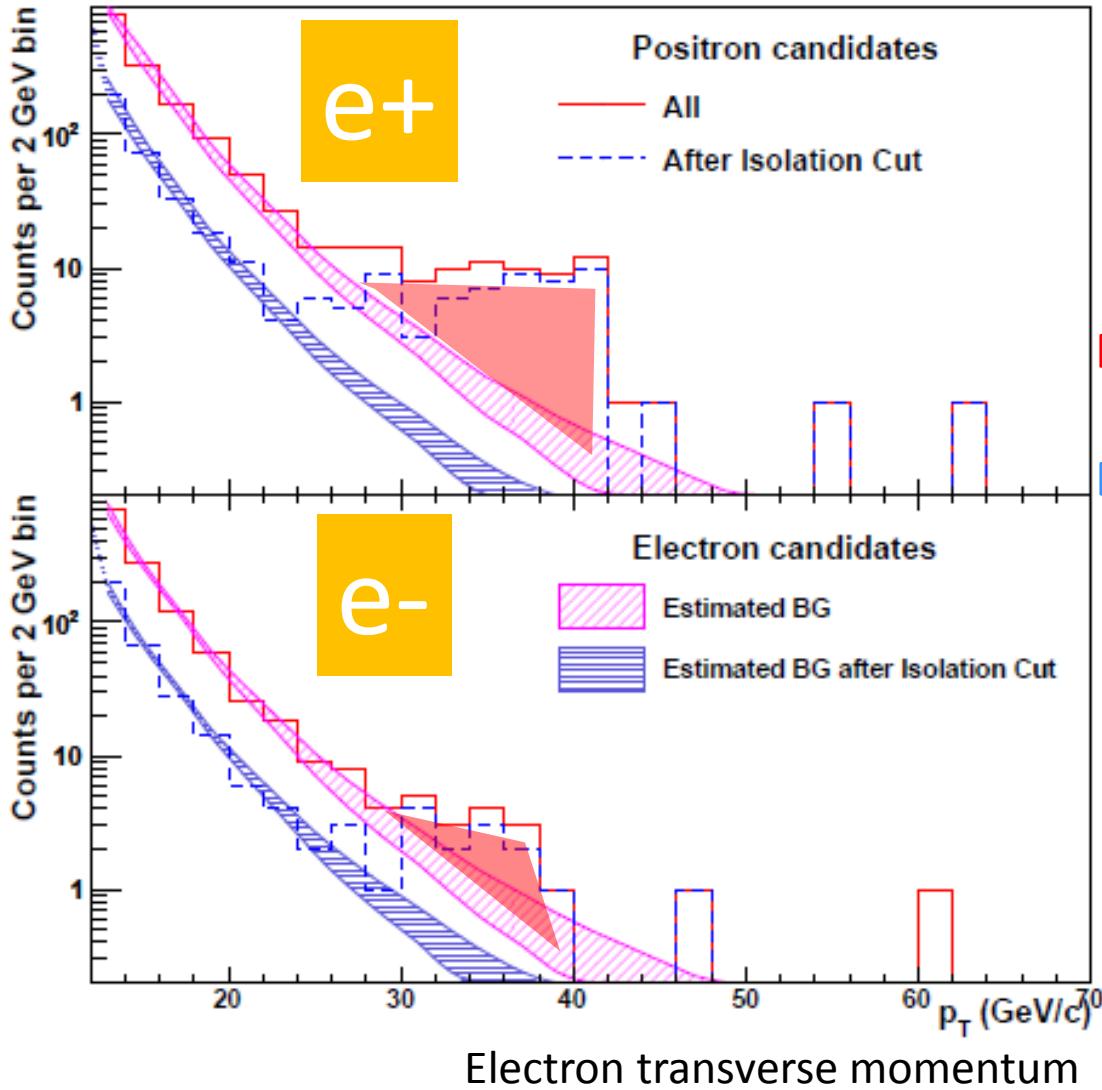
Background:

The tail of QCD interactions. The electron comes with other particles.
→ An isolation cut reduces those BG.

High energy,
isolated



W boson signal



Run9 (2009) data $\int L = 8.6/\text{pb}$

p_T distribution of electron candidates

Red histogram:

with minimum track requirements

Blue histogram:

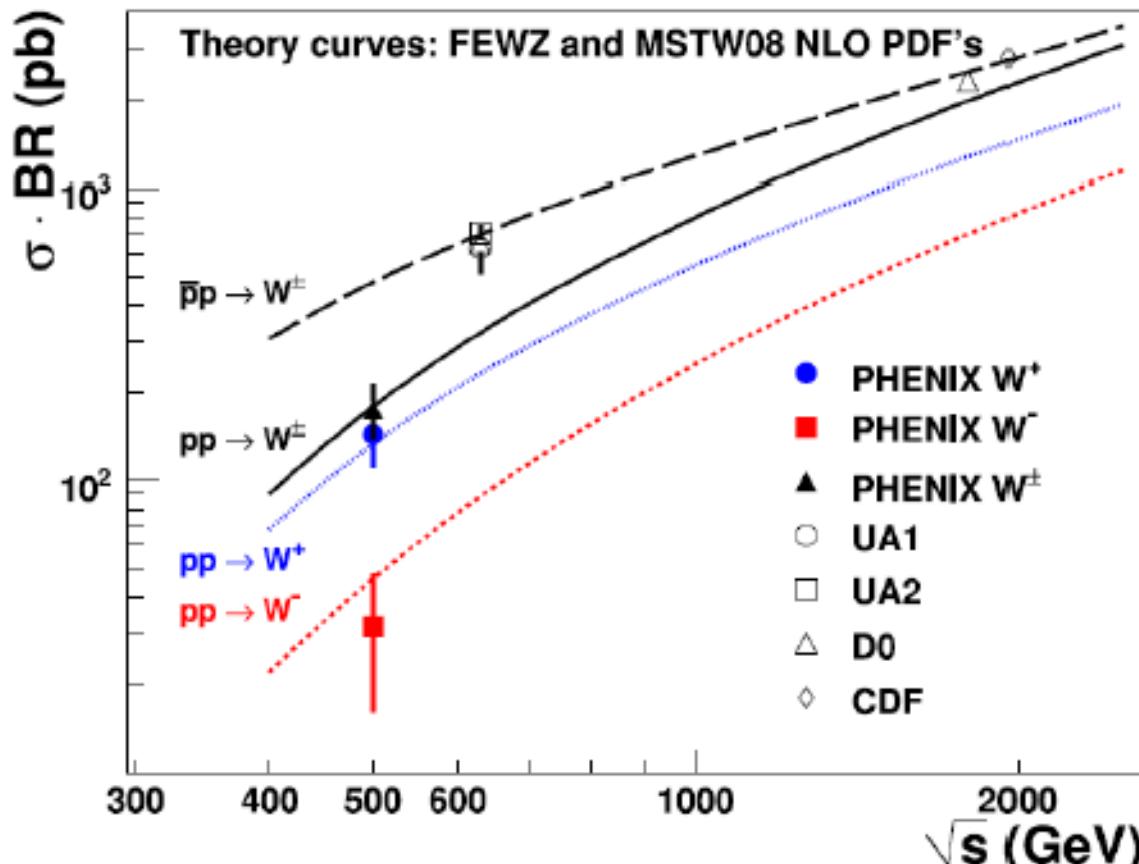
with an isolation cut

Z decay is included.

Main background :
Photon conversion
Charged hadron interaction

Convert to the total W production

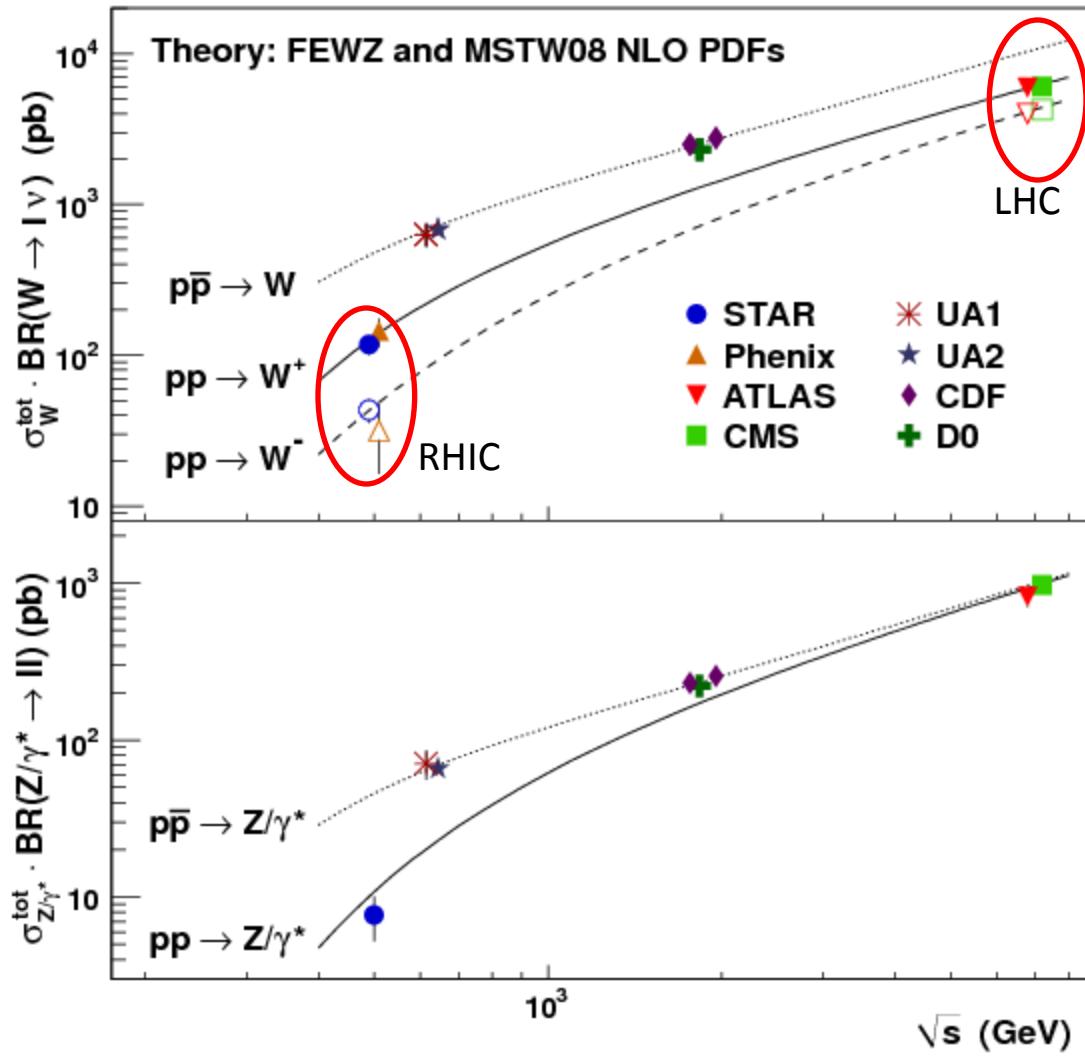
PHENIX acceptance \longrightarrow Full 4π
($pT > 30 \text{ GeV}$, $|y| < 0.35$)



Z boson contribution
+ : $\sim 7\%$, - : $\sim 30\%$
Fraction of the PHENIX
+ : $\sim 22\%$, - : $\sim 15\%$

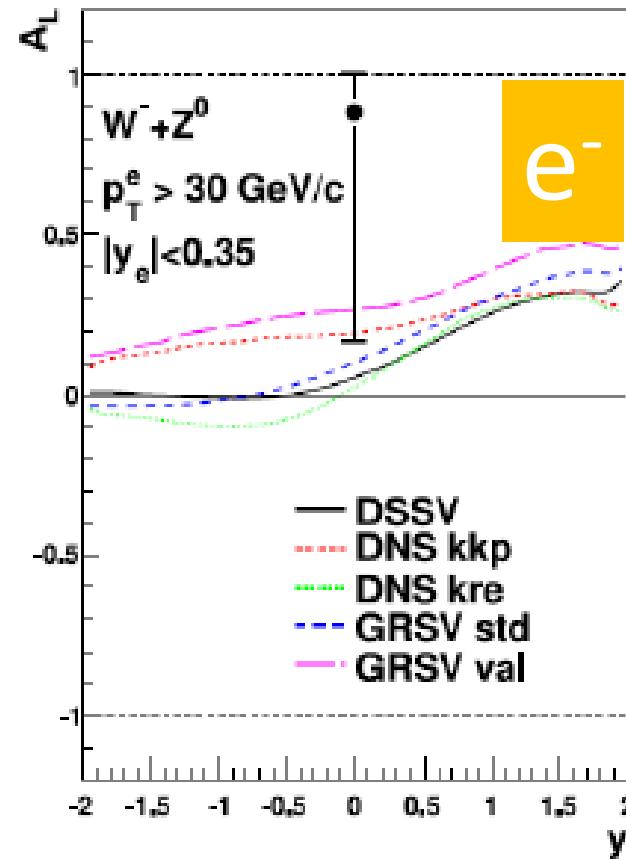
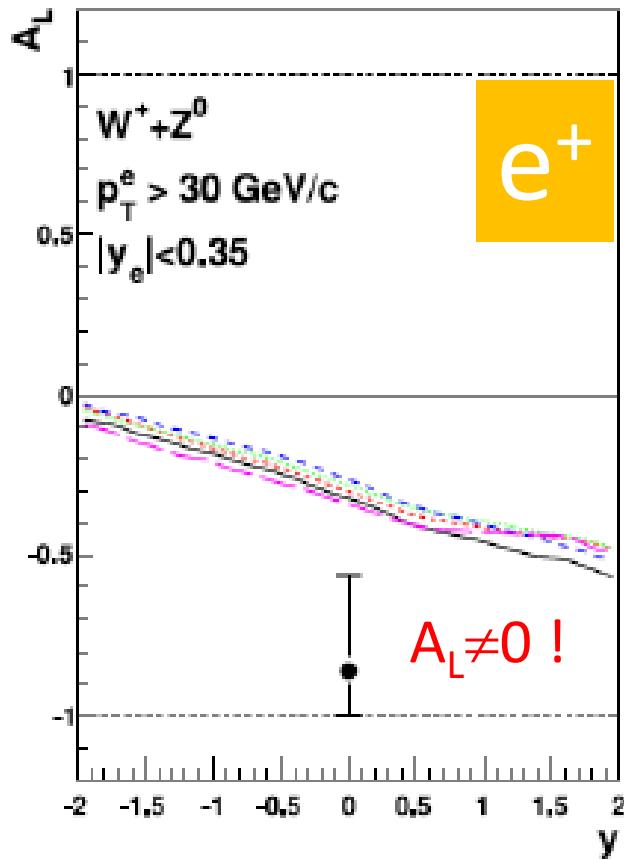
The first measurement
in $p+p$ collisions.

More recent measurements



STAR Collaboration (arXiv:1112.2980, Dec 2011)

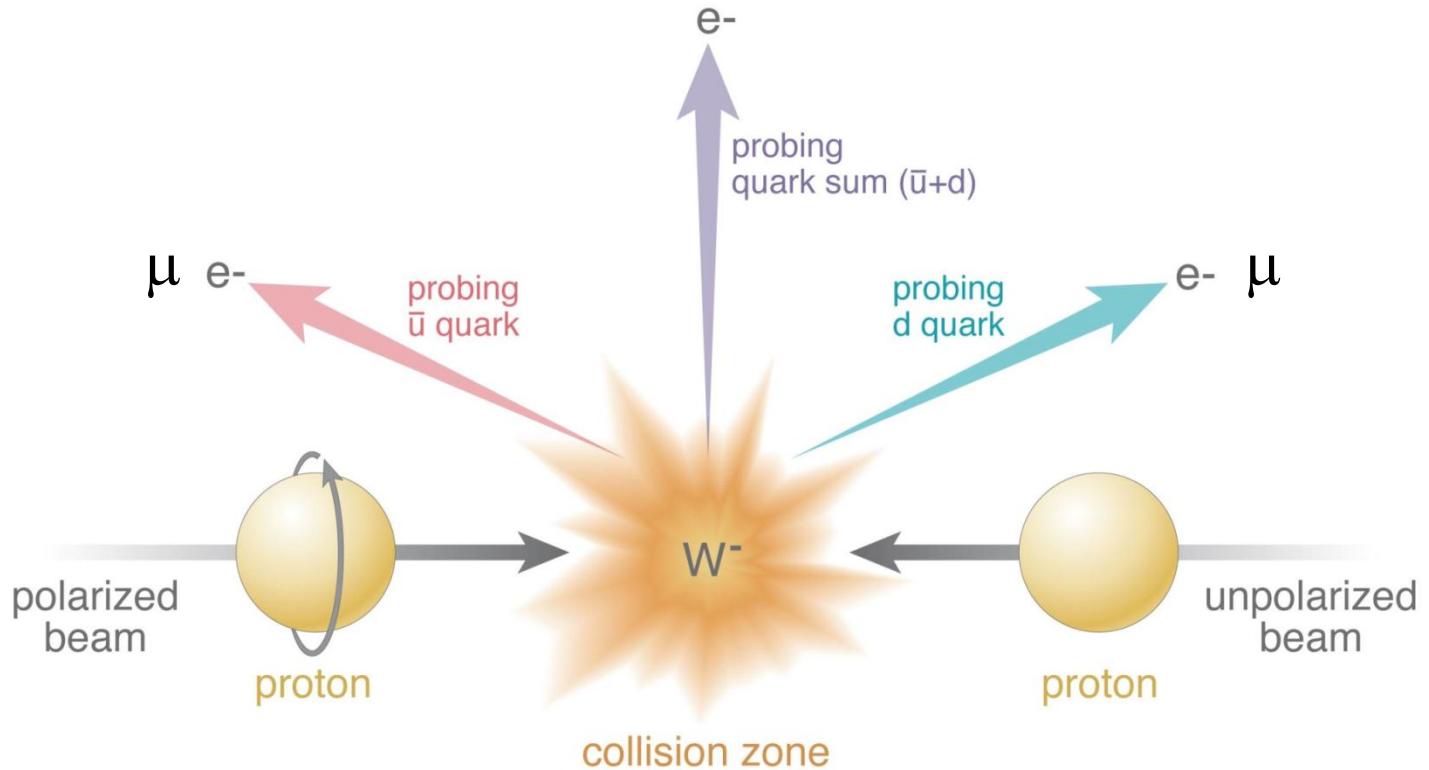
Ready for the asymmetry



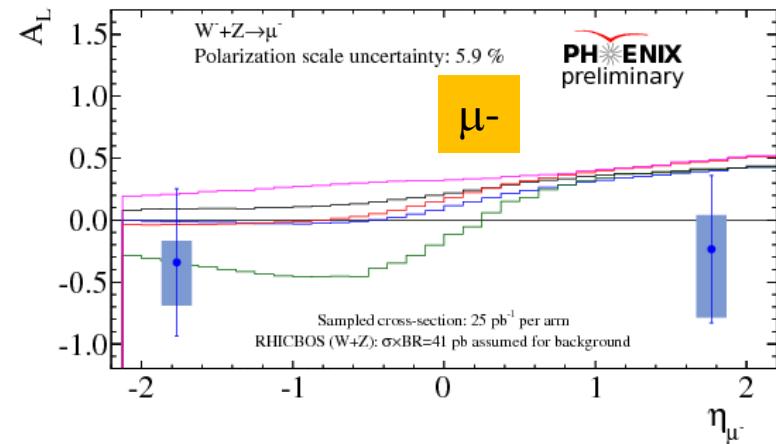
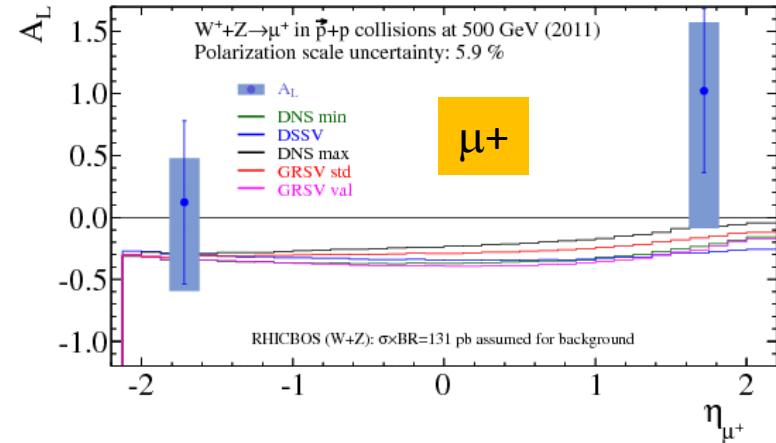
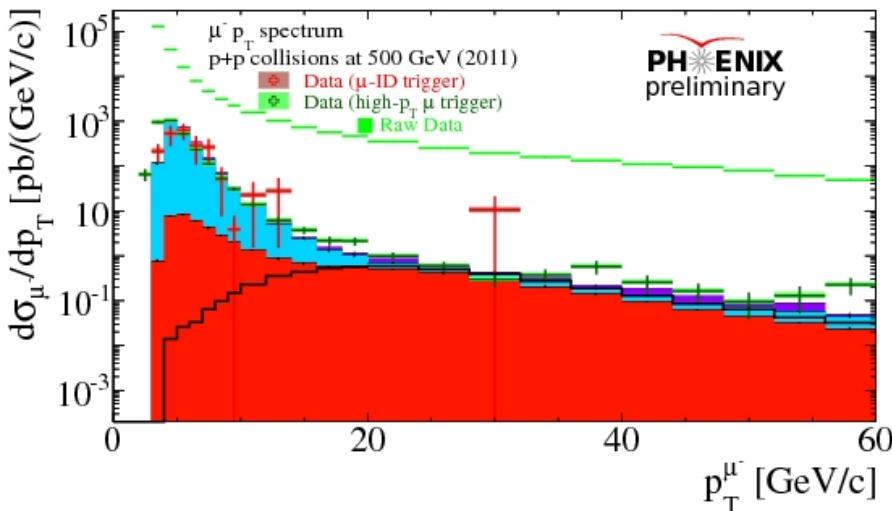
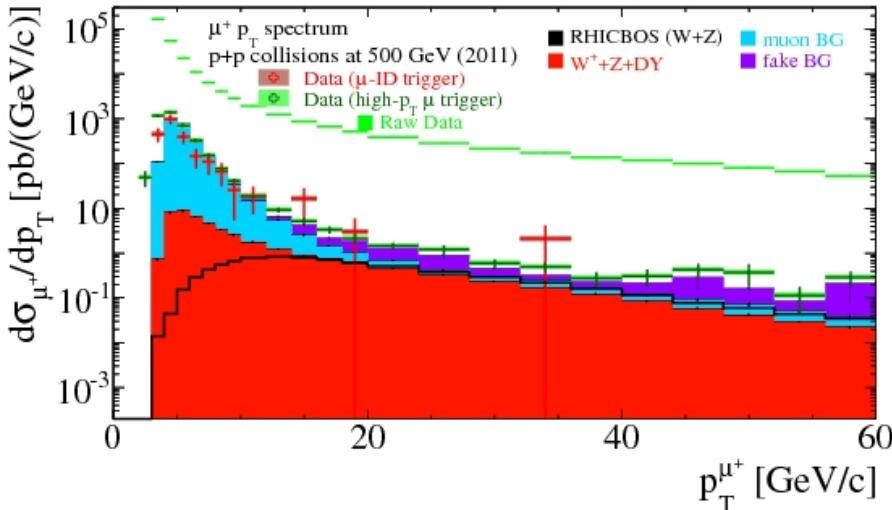
Single spin
asymmetry (A_L)
(68%CL)

Horizontal axis:
“y” corresponds to
the polar angle of
the electron.

Muon decay in forward

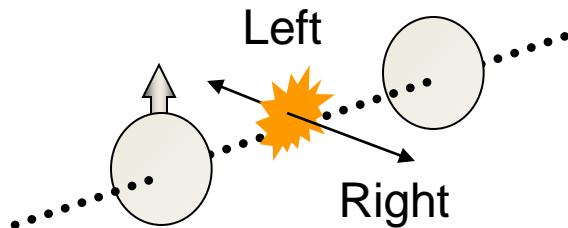
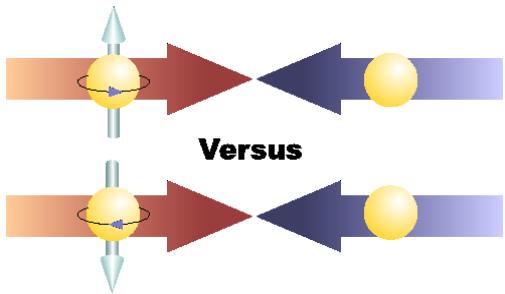


Forward $W \rightarrow \mu$ (2011 run)



The first result appeared in March.

Transverse spin asymmetry (A new way to test QCD)

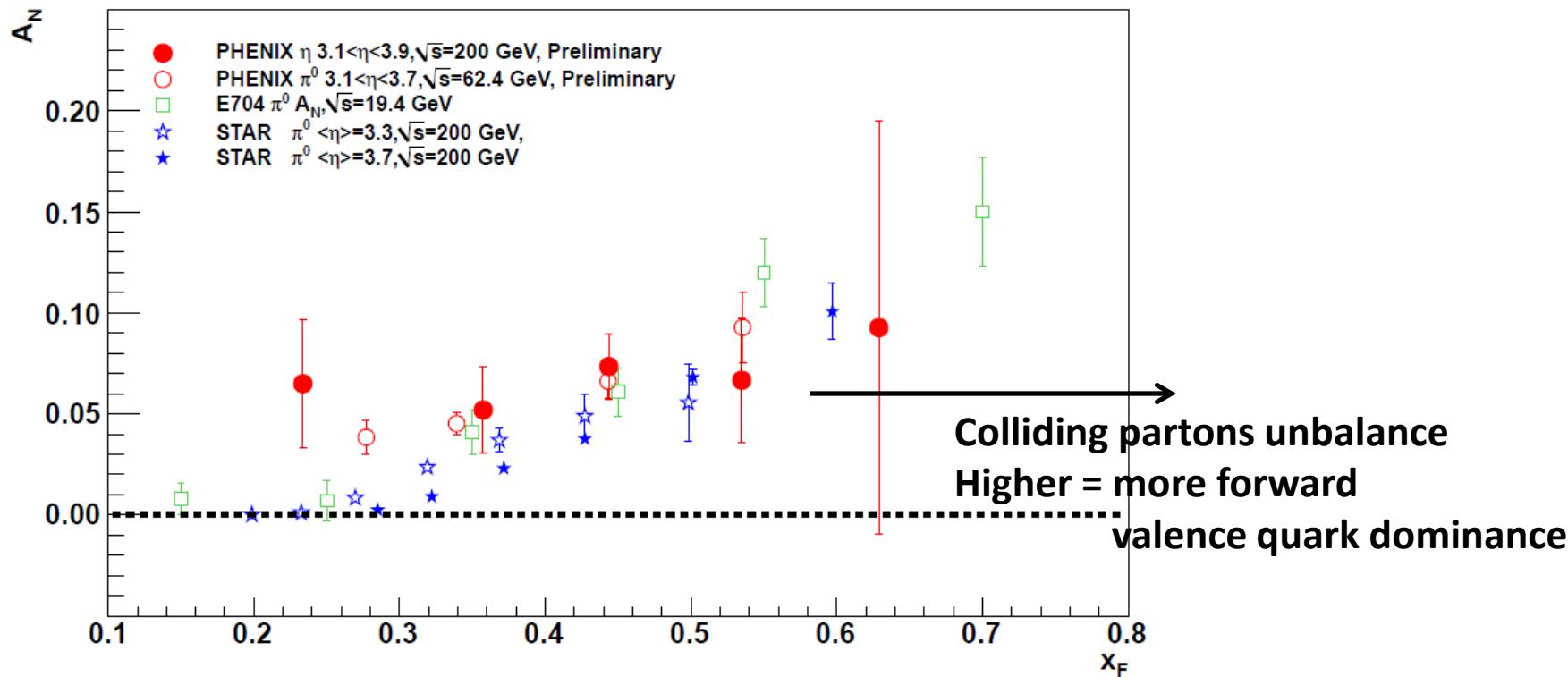


$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

- Observable: left-right asymmetry to the proton spin.

{ Single particle production
Plane formed by multi particles
others

Indication of quark transverse motion?



- Large asymmetry even at RHIC energy.
- It is not explained by the collinear framework.
→ Theory developments, Transverse motion (L)
- More experimental data are required.

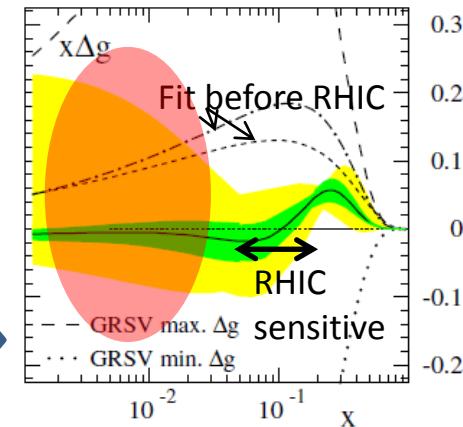
NEXT STEPS

Comments on the current status

- ΔG
 - Not large
- W-boson, (anti-)quark spin flavor decomposition
 - The program has just begun.
- Transverse spin program
 - Non-zero left-right asymmetry is observed.

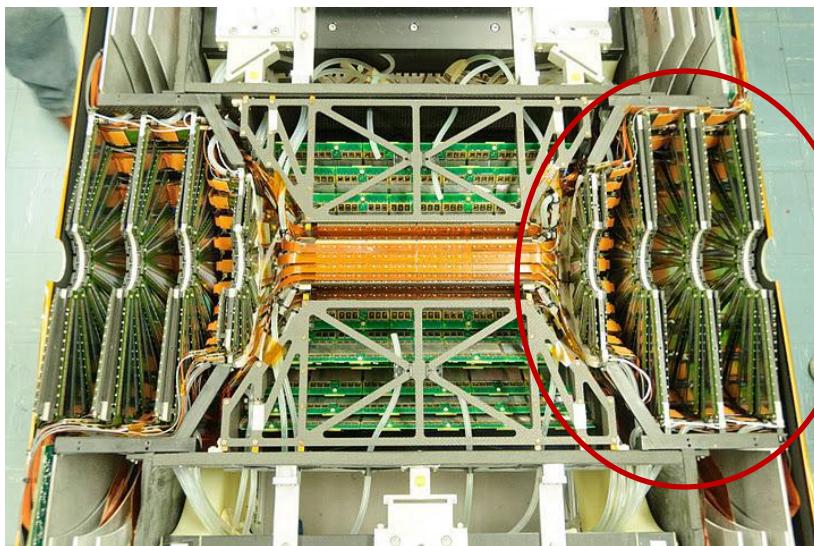
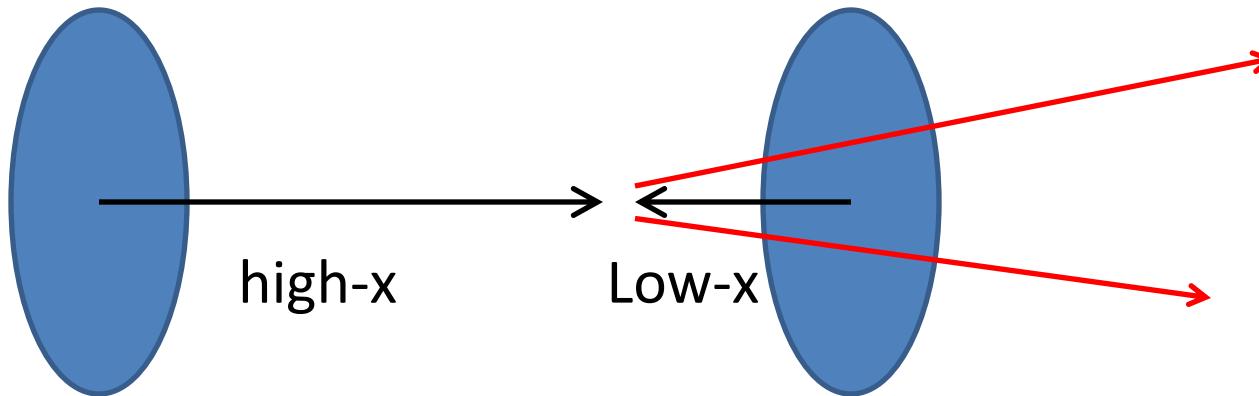
Comments on the current status

- ΔG
 - Not large (**in a limited x region**)
 - Need low- x where more gluons hide. 
 - Clean probe (e.g. direct photon) needs high statistics.
- W-boson, (anti-)quark spin flavor decomposition
 - The program has just begun.
 - Main focus for next years.
- Transverse spin program
 - Non-zero left-right asymmetry is observed **in high- x** .
 - Need to decompose many processes. 



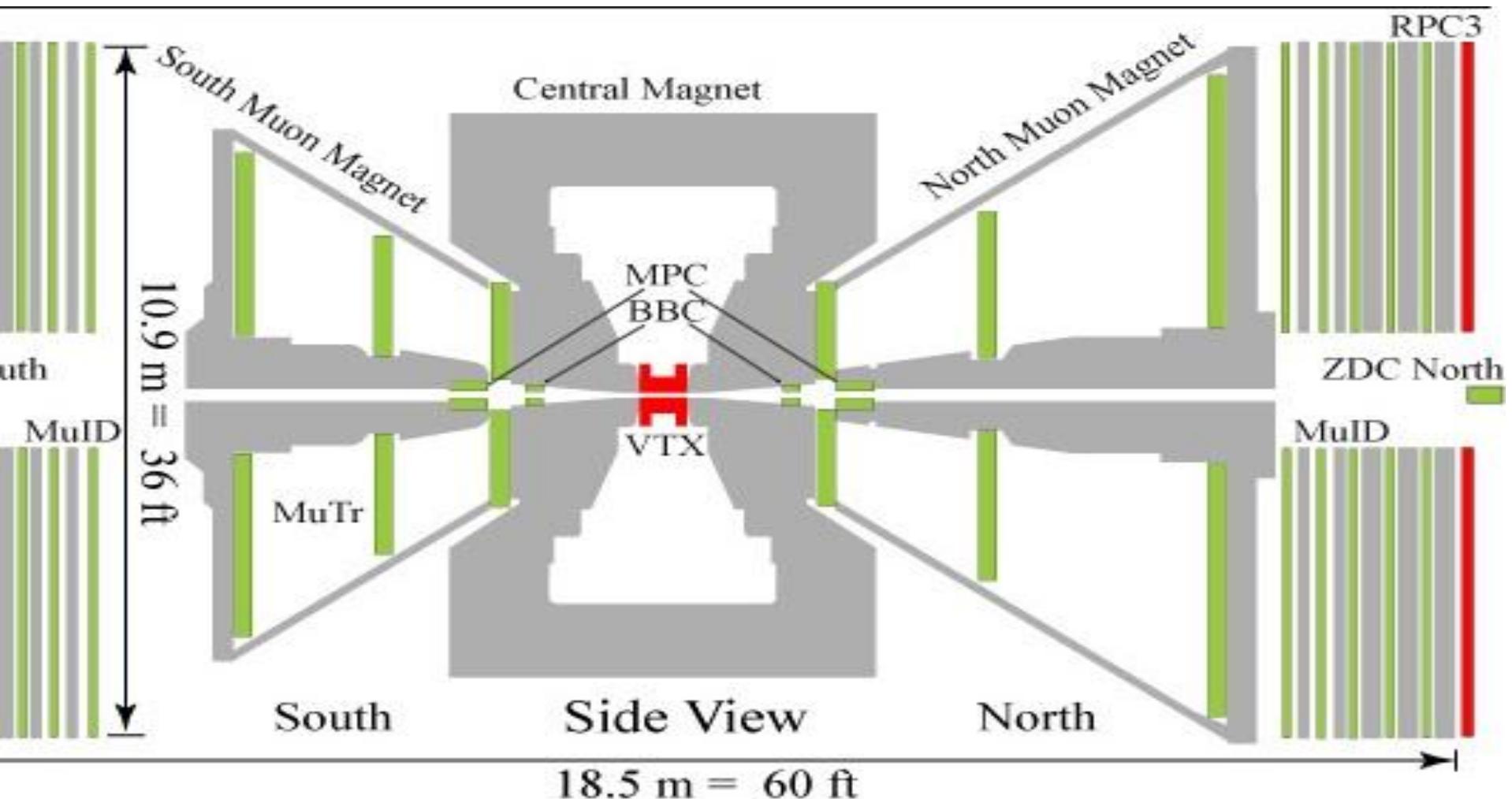


Suggests to look forward

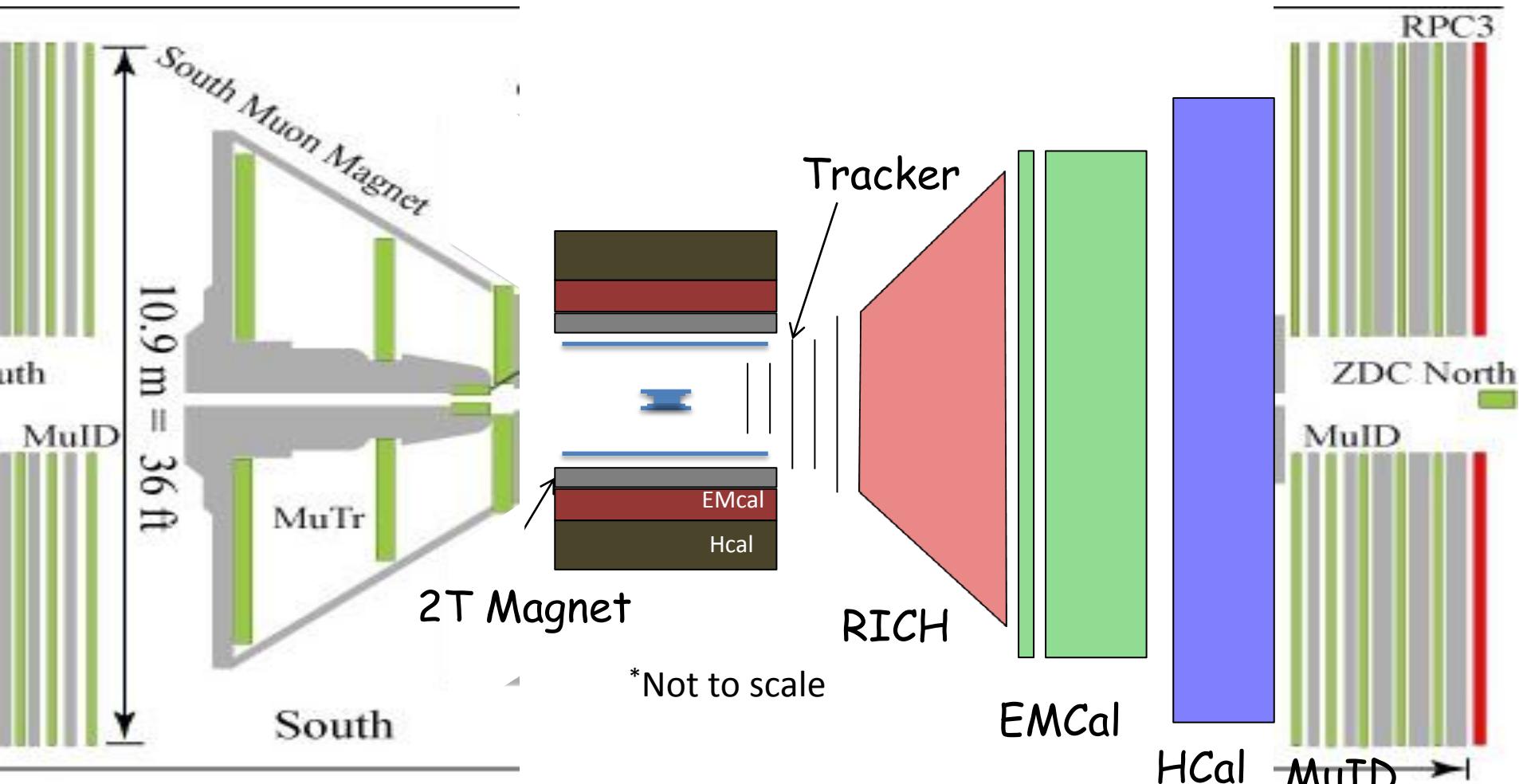


The first stage:
FVTX detector
Installed in 2012.
NMSU leads the effort.

PHENIX Design (2012)



sPHENIX discussion (late 2010's)



- Larger acceptance
- Forward detectors

Summary

- RHIC provides a unique opportunity for proton spin component.
- The W boson program for $\Delta\bar{q}$ has started.
Main stream in the next few years.
- Both ΔG and **transverse spin program** suggests to look at the forward region.
- sPHENIX (Super PHENIX) discussion is on going.

Backups

W boson analysis task force

2007 RSC(11/30) Okada

2008 JPS (9/23) Okada

Task force (Chiu, Okada)	(09-10-06)	DNP/JPS (10/13) Karatsu	(10-04-07)	DIS2010 (4/19) Chiu
	(09-10-20)		(10-04-13)	
(09-01-23)	(09-10-27)		(10-04-20)	
(09-02-05)	(09-11-03)		(10-04-27)	
(09-02-13)	(09-11-09)		(10-05-04)	
(09-02-27)	(09-11-16)	RHIC spin collaboration	(10-05-11)	
(09-03-13)	(09-11-30)	(11/21) Okada	(10-05-18)	
(09-03-27)	(09-12-07)		(10-05-25)	
(09-04-10)	(09-12-14)		(10-06-09)	
(09-05-07)	(09-12-22)		(10-06-16)	
(09-05-21)	User's meeting	WWND (1/2) Kawall	(10-06-29)	W-BNL (6/24) Kawall
(09-06-12)	(6/1) Karatsu		(10-07-07)	
(09-07-14)		PHENIX collaboration	(10-07-15)	
(09-07-21)		(1/15) Okada	(10-07-20)	ICHEP (7/21) Haggerty
(09-07-27)			(10-07-27)	
(09-08-04)	(10-02-02)	Preliminary stamp	(10-08-03)	
(09-08-11)	(10-02-24)	APS (2/13) Haggerty	(10-08-06)	
(09-08-18)	(10-03-02)	LLWI (2/14) Okada	(10-08-17)	
(09-08-25)	(10-03-09)	High PT2010 (3/17) Karatsu	8/17- 9/4 ppg meetings everyday.	
(09-09-01)	(10-03-16)		arXiv:1009.0505	Paper submission
(09-09-08)	(10-03-23)			
(09-09-15)	(10-03-30)			
(09-09-23)			JPS (9/11) Okada	
(09-09-29)			SPIN (9/27) Okada	

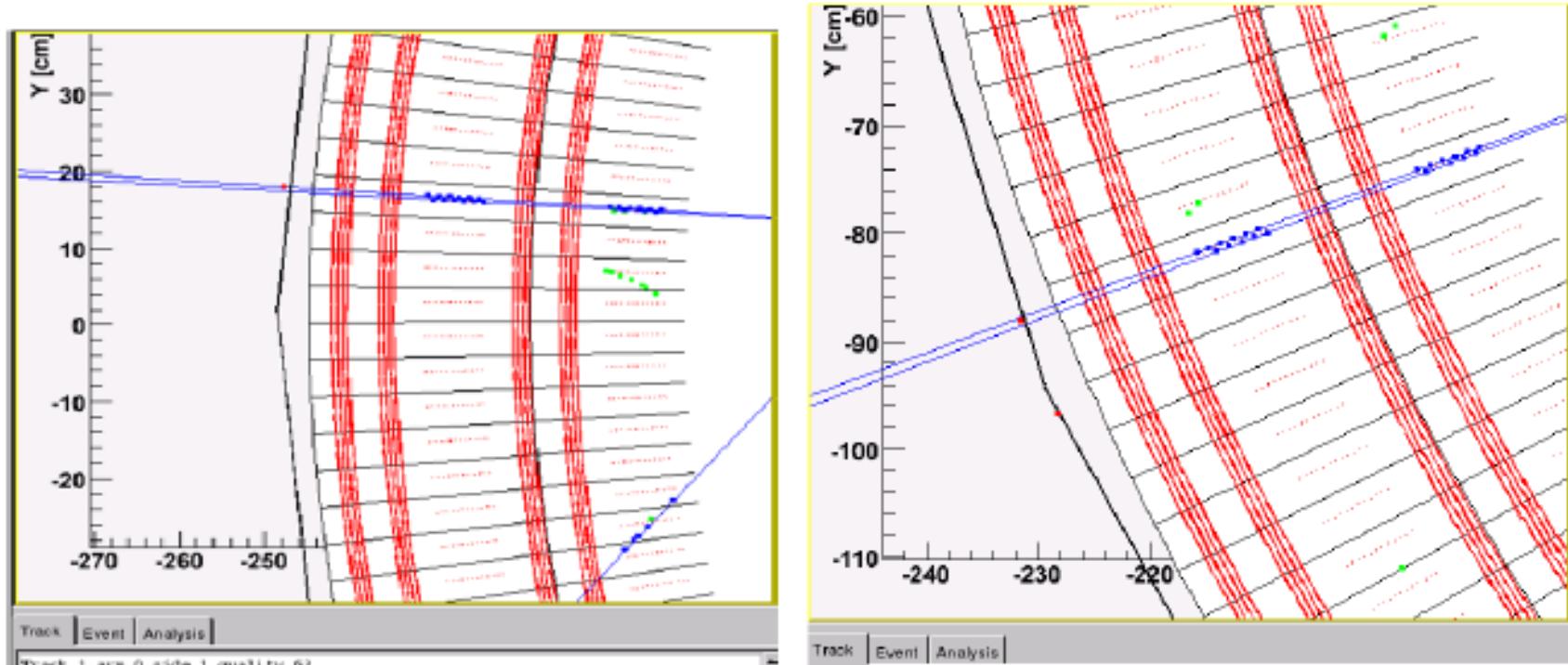
**Data
collection**

Run9 500GeV

Preliminary stamp

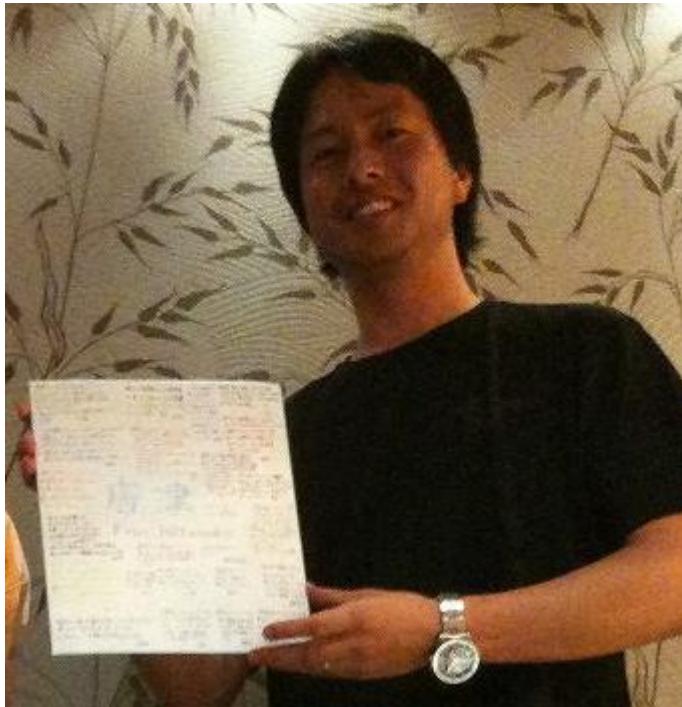
Feb, 2011 Publication

Example of unused candidates



- Ghost in Drift chamber
- Rejected because of charge unknown
- It is close to the detector limitation

Dr. Kenichi Karatsu



Kenichi Karatsu:

"Measurement of Cross Section and Single Spin Asymmetries of W-Boson Production in Polarized pp Collisions at $\sqrt{s}=500$ GeV",
Ph.D. thesis at Kyoto University, 2011,

Spin Physics Channels

Physics Channel	track.	PID	EMC	HCAL	Muons	$\int Ldt$ [pb-1]
AN in Drell-Yan (Sivers)	+		+	-	+	200-1000
Collins AT in jets (Trversity)	+	+	+	+	-	50
IFF AT in jets	+	+	+	+	-	50
AN for jets (Sivers)	+	-	+	+	-	20
AN for direct photons (Sivers)	+	-	+	-	-	200
AN with heavy flavor	+ (vtx)	+	+	-	+	100
ALL for (di-) jets (low x)	+	-	+	+	-	200
AL for W	+	-	+	+	+	1000

All channels but Ws will work well with an acceptance of $2 < \eta < 4$

Recorded Data



Year	\sqrt{s} (GeV)	L (pb^{-1})	P	FoM ($P^4 L$)	FoM ($P^2 L$)
2003	200	0.35	27%	0.0019	
2004	200	0.12	40%	0.0031	
2005	200	3.4	49%	0.20	
2006	200	7.5	57%	0.79	
2006	62.4	0.08	48%	0.0042	
2009	500	10	40%	0.26	1.6
2009	200	14	57%	1.4	
2011	500	26.7	48%	1.4	6.1

Runs 12+13 expected 300 pb^{-1} (500 GeV)

Recorded Data



Year	\sqrt{s} (GeV)	L (pb $^{-1}$)	P	FoM (P 2 L)
2002	200	0.15	15%	0.0034
2005	200	0.16	47%	0.035
2006	200	2.7	51%	0.7
2006	62.4	0.02	48%	0.0046
2008	200	5.2	46%	1.1

Runs 12+13 expected 33 pb $^{-1}$